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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GEOLOGICAL OBSERVATIONS IN THE LEBANON MOUNTAINS OF WESTERN ASIA

BY H. E. VOKES

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ABSTRACT

The Lebanon Mountains are a north-south-trending range at the eastern end of the Mediterranean Sea. Investigations were conducted in this area during the summer of 1940. Because of military restrictions it was not possible to work in the northern portion of the range, and the following observations are based on field work in the southern sections.

Although Tertiary rocks occur on their margins, the Lebanon Mountains are composed wholly of Upper Jurassic and Cretaceous strata. The Jurassic is represented by Kimmeridgian and Portlandian (?) deposits; the Cretaceous by the Neocomian, Aptian, Albian, and Cenomanian. Turonian and Senonian beds have been recognized on the flanks but are absent in the central portion of the range.

All the sediments except the Neocomian are marine. The Neocomian are principally continental red sandstones with nodules of iron and lenses of lignite. Casts of plant stems are abundant, and dinosaur bones were found.

The range is bounded on both sides by prominent faults. A strong transverse fault zone runs east-west from the region of Beirut at least as far as Jebel Kenaise. North of this the range is essentially a horst of Jurassic rocks with Cretaceous deposits forming the ridges and peaks; to the south it is a tilted block with the greater uplift on the eastern side, where the Jurassic crops out, and with Cretaceous deposits dipping gently off toward the west.

INTRODUCTION

During the summer of 1940 the writer studied the stratigraphy and invertebrate paleontology of the Lebanon Mountains in the Republic of Lebanon, one of the smaller subdivisions of the French mandated territory of Syria. This investigation was a co-operative study participated in by The American Museum of Natural History and The American University of Beirut and was financed by a fellowship grant of the John Simon Guggenheim Memorial Foundation.

The entry of Italy into the war while the writer was in the field closed the Mediterranean Sea to travel by Americans and made it impossible to ship the bulk of the material collected to the United States for study, and this must remain in Beirut until the end of the present struggle. As there is no way of determining when this collection will be released for study it is thought desirable to record at this time certain geological and stratigraphical conclusions arrived at during the work in the field which in all probability will not be subject to revision after a detailed study of the faunas.

ACKNOWLEDGMENTS

This study was undertaken on a fellowship grant of the John Simon Guggenheim Memorial Foundation. The writer is greatly indebted to the Trustees of the foundation and to its Secretary-General, Mr. Henry Allen Moe; to the authorities of The American Museum of Natural History, who permitted him to undertake this study; to President Bayard Dodge of the American University of Beirut and to many friends among its faculty for their many kindnesses, aid and hospitality in Beirut, as well as in the field. Mr. Louis Dubertret, the government geologist, aided in the interpretation of field problems and indicated sections where assistance in solving critical problems might be sought.

LOCATION AND AREA STUDIED

The Lebanon Mountains are an essentially north- and south-trending coastal range located near the central part of the eastern end of the

Mediterranean Sea. Approximately 100 miles long and 15 to 25 miles wide, the range is generally considered as being bounded on the south by the valley of the lower course of the Leontes River or Nahr-el-Kasmieh and on the north by the valley of the Nahr-el-Kébir. The main struc-

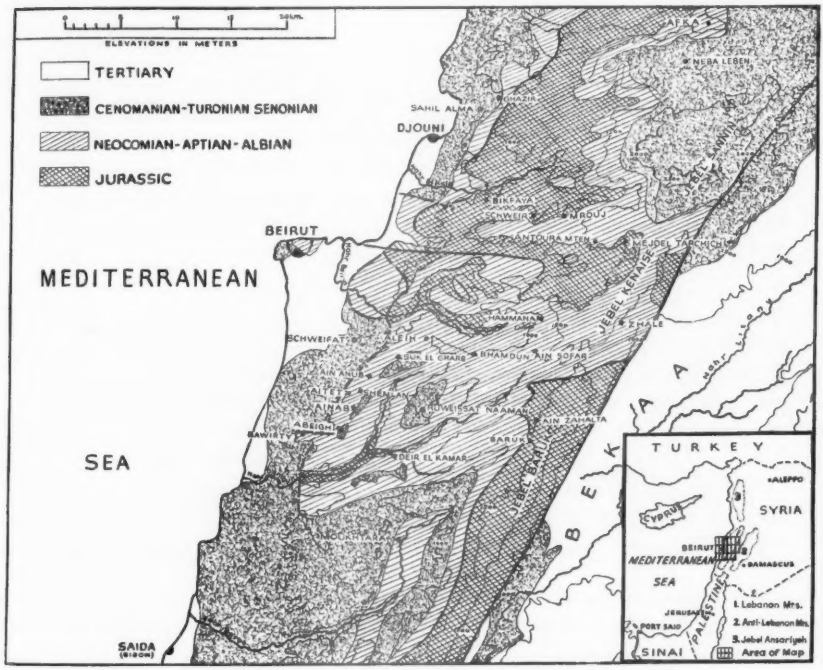
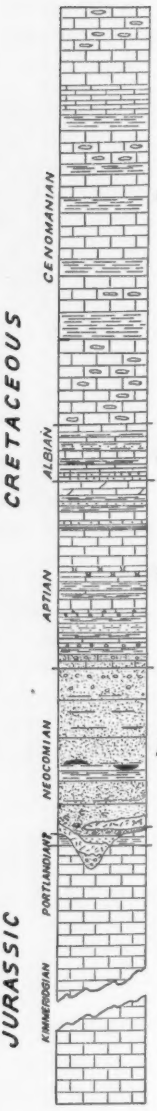


FIGURE 1.—*Geologic sketch map of the central Lebanon Mountains*

tural elements of the range, however, continue southward beyond the deep valley of the Leontes, but to the north the mountain mass breaks down to form a broad, rolling transverse valley separating the Lebanon Mountains from those of the Jebel Ansariyeh (or "Massif Alaouite"). On the western side the range rises abruptly from the sea and descends with equal abruptness on the east to the great central depression of the Bekaa.

Military restrictions and lack of time prohibited any attempt at a detailed study of the northern part of the range, and the prohibition by the authorities of the use of maps in the field prevented detailed mapping. The accompanying map (Fig. 1) is, therefore, essentially a



Lt. gray to white ls. and calcareous shales; abundant large siliceous concretions. Fossils abundant at a few localities: Ammonites, *"Radiolites," Nerinea*, etc.

Gray ls., light gray calc. sh., *Heteraster delgadoi, Knemiceras syriacum.*

"Cardium bank"- brown sandy ls. with molds of pelecypods.

Ls. dolomitic ls., ss., sh.,–Fossils abundant *Orbitolina, Heteraster oblongus syriacus. Radiolites plicatus.*

Volcanic ash.

Massive blue-gray ls. 175± feet thick – few fossils.

Buff to gray ls. some oölitic; gray sh.;*Heteraster oblongus syriacus, molluscs.*

Buff and gray ss., gray sh.,– Fossils abundant at some localities.

Red ss. and shales with abundant iron concretions, and thin lignites; basalt flows near base.

Poorly preserved plant remains and dinosaur bones.

Oölitic ls. and gray sh.-Fossils abundant. *Balanocidaris glandarius* beds.

Heavy blue gray ls. – Few, poorly preserved fossils.

FIGURE 2.—*Geologic section in the central Lebanon Mountains*

diagrammatic representation of the distribution of the formations in the area examined in some detail and from which the great bulk of the fossils were obtained.

STRATIGRAPHY

INTRODUCTORY STATEMENT

Although Tertiary rocks (Eocene, Miocene, and Pliocene) occur on the flanks of the range, the main mass of the Lebanon Mountains appears to be composed wholly of Upper Jurassic and Lower and Middle Cretaceous deposits (Fig. 2). Older Jurassic rocks have been reported on the slopes of Mount Hermon in the southern part of the Anti-Lebanon by Noetling (1885) and more recently by Vautrin (1934; *see also* Vautrin *in* Dubertret, 1933, p. 289) who reports an extensive section of Lower and Middle Jurassic deposits there. None of these are to be found in the Lebanon where the lowest Jurassic strata exposed are referred to the Kimmeridgian.

JURASSIC FORMATIONS OF THE LEBANON MOUNTAINS

Kimmeridgian deposits.—These oldest deposits found within the Lebanon Mountains are represented by over 1500 feet of blue-gray limestones, generally heavily bedded, and in places somewhat dolomitic. The base of the formation is nowhere observed unless it is to be found on Mount Hermon, where the section is disturbed by faulting and obscured by lava flows. In places at the top of the formation a thin zone of ash and basalt is overlain by a thinner zone of brecciated and nodular limestone. The basalts are well exposed in road cuts near Bikfaya. Where observed the thickness of this zone was not over 50 feet and on the average was approximately 30 feet.

Fossils are not abundant in these deposits and are generally too greatly silicified to be determinable. Masses of what appear to have been originally coral heads were observed at several localities and seem to have been a dominant element in the fauna. Two large specimens of the pelecypod *Ceratomya excentrica* (Roemer) were collected from the upper brecciated nodular zone near the village of Antoura-Mten on the slopes of Jebel Sannin. In Europe this species is known from the Argovian and the Kimmeridgian. It is also present in collections from the Kimmeridgian deposits of Harrar Province, Ethiopia, in The American Museum of Natural History.

Portlandian (?) deposits.—The highest Jurassic deposit found in the Lebanon is a thin series of sandy-yellow limestones and clays with oölitic limestones above. This formation has been considerably affected by post-depositional, pre-Cretaceous erosion and is absent in many localities. Where present the thickness is variable. Near Bikfaya and southeast of Mrouj the formation is slightly more than 50 feet thick.

Fossils are generally abundant and well-preserved. The fauna is not large, however, the collections containing numerous representatives of a few species. The most characteristic element is the large spines of the echinoid *Balanocidaris glandaria* (Lang), and the horizon has been referred to as the "Calcaire a *Cidaris glandaria*" by Fraas (1878), Noetling (1886), and Zumoffen (1926). At several localities, notably southeast of Mrouj, limestones are composed almost wholly of the remains of stromatoporoids, including *Burgundia ramosa* Pfender and *Lovcenipora* sp. cf. *vinassei* Giattini. The collections from this horizon include: [1]

Sponges
Burgundia ramosa Pfender
Lovcenipora sp. cf. *vinassei* Giattini
Hexacoralla (several species)
Apiocrinus cretaceus Fraas
Balanocidaris glandaria (Lang)
Hemicidaris sp.
Terebratula bisuffarcinata Schlotheim
T. subsella Leymerie
(?) T. Bauhini Etallon
Kingena (?) sp.
Ostrea (Alectryonia) sp.
Lima libanensis Krumbeck
Pecten sp.
Mytilus sp.
Natica dido Krumbeck

POST-JURASSIC, PRE-CRETACEOUS UNCONFORMITY

There is a pronounced unconformity between the Jurassic and Cretaceous deposits, and during this interval deep channels were formed which penetrate well down into the Kimmeridgian limestone in many places and are responsible for the discontinuous distribution and variable thickness of the Portlandian (?) strata. The red sandstones and shales of the earliest Cretaceous deposits are in marked contrast with the more drab Jurassic strata and, in the field, serve to emphasize the physical features of the unconformity.

CRETACEOUS FORMATIONS OF THE LEBANON MOUNTAINS

Neocomian deposits.—Cretaceous deposition in the Lebanon Mountains began under continental conditions, and the lowest series of strata consists of argillaceous bright red and purple sandstones with interstratified red and varicolored shales and with lenses of gray and black shales containing lignite. The sandstones are composed of poorly sorted, angular quartz grains, usually only slightly indurated and commonly cemented by an iron oxide film. In places, as on the road between Baruk and Ain Zahalta, there are horizons of soft dune sand in which the grains show the typical rounding and pitting of wind-borne material.

Basaltic flows and ash beds occur throughout the formation, generally toward the base. At a number of localities thin basalt flows are also present at the contact with the overlying Aptian. Zumoffen (1926) generally refers these to the latter stage, but their field relationships indi-

[1] It is to be emphasized that these are field determinations subject to revision upon receipt and study of the collections.

cate that they are almost certainly more closely related to the continental Neocomian deposits. In general these flows are seldom more than 4 or 5 feet thick but toward the northern part of the range they tend to be much thicker.

Large ironstone concretions occur throughout the red sandstones. At some localities these were sufficiently numerous to warrant their being collected and smelted for their iron content. One of these, at Merdchibah near Mrouj, was worked until about 10 years ago. According to Zumoffen (1926, p. 57) the minerals smelted were ochraceous limonite, spathic iron, and ferruginous yellow ochre; analyses made in Cairo indicated a 50 to 60 per cent iron content. The smelting of these concretions is said to date back to the time of the Roman occupation.

The lignites are generally very thin and of poor quality. Nevertheless, during the last World War, German engineers attempted to develop them, and during 1917 and 1918 about 100 tons of the lignite were mined from several localities including Abeigh, Arsoun, Aramoun, Bzebdin, and Djezzine. They have not been worked since.

Fossils are very rare. Most abundant are casts of wood and the impressions of bark. These were found in virtually every outcrop, but none showed any structure or other evidence permitting generic or specific determination. A few scattered dinosaur bones were found. These are generally only isolated vertebrae, but one distal end of a humerus of a large sauropod is in the collection of The American University of Beirut. This was determined by Sir Arthur Smith Woodward as being of a *Diplodocus*-like type. The age reference of this horizon is based primarily upon its relationship to the overlying deposits. In a broad sense this formation appears to be correlative with the Nubian sandstone of Egypt and the Sinai Peninsula.

North of the Lebanon Mountains these Neocomian deposits are absent in the Jebel Ansariyeh and Jebel Akra (Dubertret, 1937a) and in the Lebanon itself they thin toward the north, being but 30 meters thick at Sir (Dubertret, 1937b, p. 52). In the area examined they tend to be thinner in the center of the range than toward the flanks. The thickest section observed is at Ain Zahalta where the formation is about 1000 feet thick.

Deposition appears to have been continuous from Neocomian to Aptian in this area. The Aptian deposits were formed under marine conditions, and the contact between the two horizons should be drawn at the point where these conditions first obtained; this, however, is difficult to determine.

Aptian deposits.—The deposits of Aptian age in the Lebanon Mountains fall naturally into three divisions: (1) a lower zone of sandstones

passing up into shales and limestones, (2) a massive, cliff-forming limestone, and (3) an upper zone of sandstones and shaly limestones.

The lower zone is somewhat variable in thickness but averages about 250 feet in the area studied. The lowest strata here referred to the Aptian are so coarsely pisolitic as to resemble great banks of marbles. Some of the individual concretions are as much as an inch in diameter. These pisolitic beds are particularly well developed in the central and eastern part of the range, and near Baruk the road cuts show more than 20 feet of strata composed almost entirely of them. Dubertret (1937b, p. 55) refers these beds to the Neocomian, but, if the base of the Aptian be drawn at the point where marine conditions first obtained, it is here held that this zone is best referred to the Aptian.

Above the pisolitic zone the lower Aptian consists of marine sandstones, "siltstones," and sandy shales grading up into sandy shales and limestones. Fossils are relatively abundant in the lower marine sands and silts, while some thin interbedded lignitiferous sandstones suggest shoaling conditions. The majority of the fossils described from Abeigh by Conrad (1852) and Hamlin (1884) and from the "Olive Locality" of Abeigh described by Whitfield (1891) are from the lower sandstones of this zone. The large fauna (Whitfield lists 72 species from the "Olive Locality") of this horizon is almost wholly composed of pelecypods and gastropods, but the echinoid *Heteraster oblongus* Brongniart var. *syriacus* de Loriol is the most characteristic form found throughout the Aptian deposits. The fauna of these lower sandstones includes:

Heteraster oblongus syriacus de Loriol
Trigonia syriaca Conrad (Fraas)
T. lewisi Blanckenhorn
Protocardium judaicum (Hamlin)
P. birdanum Whitfield
"Cardium" bewertense Whitfield
Ostrea alicula Hamlin
O. boussingaulti d'Orbigny
Odostomopsis abeihensis (Blanckenhorn)
Tylostoma abeihensis (Böhm)
Amauropsis subcanaliculata (Hamlin)
A. abeihensis (Hamlin)
Coronatica ornata (Fraas)
Cerithiopsis syriacum (Blanckenhorn)
Ostrea dieneri Blanckenhorn
Gervillia trapezoidalis Whitfield
Isognomon orientalis (Hamlin)
Cardita lacunar Hamlin
Anomia subobliqua Conrad
Gonodon (?) hebes Hamlin
Cytherea libanotica (Fraas)
Platopis triangularis Whitfield
Tancredia (?) abeihensis (Conrad)
Corbula naearoides Blanckenhorn
C. aligera Hamlin
C. olivae Whitfield
"Cerithium" fraasi Blanckenhorn
"C." libanoticum (Fraas)
"C." noetlingi Blanckenhorn
Terebralia (Pyrazisinus) orientalis (Conrad)
Pyrazus acutecostatum (Blanckenhorn)
Potamides distortus Whitfield
Glauconia strombiformis (Schlotheim)
Colostracon lewisi (Fraas)
"Turritella" damesi Blanckenhorn
"T." kokeni Blanckenhorn
"Epitonium" novemvaricosum (Whitfield)
Nerita abeihensis Whitfield
N. bidens Whitfield
N. pagoda Whitfield
Vanikoro neritopsoides Blanckenhorn
Turbo moreli Fraas

A higher horizon, near the center of the lower zones, carries a fauna marked by great numbers of *Nerinea schickii* Fraas. *Trigonia distans*

Conrad is associated with this form. Some of the higher limestones of this lower member carry abundant *Orbitolina lenticularis* Blum.

The massive cliff-forming limestone member of the Aptian is one of the most widespread stratigraphic units in the Lebanon Mountains. It is composed mainly of massive, light-gray to yellowish limestones in beds up to 30 feet thick with intercalated thinner brecciated limestones and greenish friable clays. The massive beds are relatively unfossiliferous and stand out as gray cliffs which form a prominent topographic feature and are a guide horizon for stratigraphic studies throughout the Lebanon. As in the case of the lower member, this horizon tends to be thinner to the north. Dubertret (1937b, p. 53) reports a thickness of 25 meters at Sir near the northern border of the range. At Ain Sofar, in the area studied, 175 feet of limestones is assigned here. This is the thickest section examined, and in general the member averages 150 to 160 feet in thickness throughout the rest of the central Lebanon.

A reconnaissance survey in the Anti-Lebanon near Jebel Ûnan and the village of Bludan suggested that this cliff-forming limestone is not well developed in that range. The faunal sequence permitted easy recognition of the horizon at which it occurs in the Lebanon, but in that area, at least, only soft nonresistant limestones were found. The section examined was in the immediate vicinity of the spring, Ain-en-Nsur. This is slightly more than 20 miles east of Ain Sofar, and the absence of this cliff horizon was one of the most striking variations noted in the section. It is surprising that a horizon which is a prominent feature of the section over a north-south distance in excess of 100 miles should apparently completely disappear over an east-west distance of 20 miles.

This cliff member has been termed the "Muraille de Blanche" or the "Banc Urgo-Aptien" by Dubertret (1937b).

The upper member of the Aptian consists of a series of fine-grained sandstones, sandy shales, and limestones. The section at Ain Sofar is typical:

	Feet
12. Brown sandstones with oölitic hematite	26
11. Hard brown sandstone	3
10. Lignitic shale and siltstone	6
9. Buff calcareous clays and limestones with minute hematite concretions and abundant internal moulds of pelecypods	13
8. Calcareous clays and limestones with *Ostrea* and *Orbitolina*	7
7. Yellow calcareous shales with abundant *Orbitolina*	3
6. Iron-rich sandstones	10
5. Purplish lignitic, volcanic (?) clay	4
4. Reddish-brown sandstones	11
3. Hard yellowish limestone composed mainly of *Orbitolina*	1
2. Bluish-green clay with a yellowish limestone in upper part; moulds of pelecypods	20
1. Hard brown limestone with abundant *Orbitolina*	7
Total	111

These upper beds are abundantly fossiliferous, the fossils being commonly the internal moulds of pelecypods. In some localities, as at Shimlan, Baisur, and Ainab there is a zone of *"Radiolites" plicatus* (Conrad), a short distance above the Muraille de Blanche. At Shimlan this is immediately overlain by a zone of *Nerinea syriaca* Conrad. One of the characteristic species throughout the upper member is *Heteraster oblongus syriacus*. Since *Heteraster oblongus* is a species of the European Aptian these beds are also referred to that horizon. The fauna of this upper member includes:

Orbitolina lenticularis Blum.
Heteraster oblongus syriacus de Loriol
Pinna cf. *cretacea* Schlotheim
Inoceramus syriacus Conrad
Ostrea dieneri Blanckenhorn
O. directa Blanckenhorn
Trigonia pseudocrenulata Noetling
T. undulocostata Blanckenhorn
Isocardia merrilli Hamlin
"Radiolites" plicatus Conrad
Horiopleura lamberti Munier-Chalmas
Cardium syriacum Conrad
Protocardium biseriatum (Conrad)
Arcopagia planissima Whitfield
"Panopea" sp. (large form)
Cyprina orientalis Hamlin
"Tellina" syriaca Conrad
Pholadomya decisa Conrad (= *P. depacta* Hamlin)
P. cf. *pedernalis* Roemer
Natica syriaca Conrad
N. indurata Conrad
Tylostoma syriaca (Conrad)
Nerinea syriaca Conrad
Strombus sp.

Albian deposits.—The base of the Albian deposits in the Lebanon Mountains is marked by a thick brown to buff sandy limestone containing abundant internal moulds of large species of pelecypods and gastropods. The most common element in the fauna is *Isocardia merrilli* Hamlin. This was early misidentified as a species of *Cardium*, and the term "*Cardium* Bank" was applied to this strata by Fraas in 1878 and has since been used. This limestone has a rather constant thickness, averaging about 40 feet throughout the central Lebanon region.

Above the "*Cardium* Bank" there occurs about 300 feet of alternating buff calcareous shales and light-gray to buff limestones. These are generally moderately fossiliferous, the fauna being marked by the echinoid *Heteraster delgadoi* de Loriol and species of the ammonite genus *Knemiceras* including *K. syriacum* (Von Buch), *K. compressum* Hyatt, and *K. uhligi* (Choffat). Representatives of this genus occasionally found in the fauna of the "*Cardium* Bank" suggest the inclusion of this stratum in the Albian, rather than with the lower strata which are also marked by abundant internal moulds of large pelecypods.

The fauna of these Albian beds includes:

Diplopodia hermonensis de Loriol
Toxaster dieneri de Loriol
Heteraster delgadoi de Loriol
Ostrea syriaca Conrad
Pinna cf. *cretacea* Schlotheim
Isocardia merrilli Hamlin
Cardium syriacum Conrad
Protocardium biseriatum (Conrad)
Cyprina orientalis Hamlin
Cytherea syriaca Conrad
Pholadomya cf. *decisa* Conrad
Natica indurata Conrad
N. cf. *gaultina* d'Orbigny

Tylostoma syriaca (Conrad)
"Strombus" crassiliratus Whitfield
Globiconcha altispira Whitfield
Knemiceras syriacum (Von Buch)
K. uhligi (Choffat)
K. compressum Hyatt

Unlike the Neocomian and the Aptian deposits which thin markedly toward the north, the Albian maintains its thickness throughout the entire coastal area of the Lebanon. Dubertret (1937a, p. 38) reports a thickness of 170 meters for the Aptian at Mechta-Helou in the Jebel Ansariyeh.

Cenomanian deposits.—The Cenomanian deposits are the highest, stratigraphically, to be found within the main mass of the Lebanon Mountains in the area studied.

These deposits consist of a series of interbedded light-gray to white limestones and hard calcareous shales. The limestones of the formation closely resemble those of the upper Albian, and it is often difficult to separate them. The most characteristic feature of these upper limestones is the occurrence of abundant large white and yellowish-white siliceous concretions. These concretions have not been observed in the limestones containing Albian fossils, and it was found practicable to draw the line between the two horizons at the base of the lowest of the concretionary limestones. As thus interpreted the Cenomanian strata in the area studied are over 1500 feet thick. The formation is thinner to the north and thickens southward into Palestine. Dubertret (1937b, p. 60) notes that it is 350 meters thick in the north of the Jebel Ansaryieh, 500 meters in the south of that range, and 500 to 1000 meters thick in the Lebanon and in Palestine.

Fossils are not widely distributed in the Cenomanian deposits, though where present they are apt to be exceedingly abundant and of varied types. The rich fauna of the "Gazelle Locality" of Whitfield (1892) is from this zone as are the remarkable fish faunas from Hackel, Hajula (Djoula), and Maifouk which have been described by Pictet (1850), Pictet and Humbert (1866), Davis (1887), and Hay (1903). A small well-preserved flora associated with an invertebrate fauna and the fossil fish was obtained from Hajula (Djoula). This, the first identifiable flora from the Lebanon Mountains, is now being studied by Professor Erling Dorf of Princeton University. The invertebrate fauna of the Cenomanian deposits of the Lebanon Mountains includes:

Echinoids (several species)
Lima tenuitesta Whitfield
Vola dutrugei (Coquand)
Neithea quinquecostata (Sowerby)
Ostrea syriaca Conrad
Alectryonia carinata Lamarck
Exogyra columba Lamarck
E. flabellata Goldfuss
E. africana Lamarck
E. cf. *olisponensis* Sharpe
Chondrodonta joannae (Choffat)
Inoceramus cf. *cripsii* Mantell
Cardium pauli Choffat
Caprinula cedrorum (Blanckenhorn)
Delphinula porteri Blanckenhorn
Pileolus sphaerulitum Blanckenhorn
Nerinea cochleaeformis Conrad
"Cerithium" rustemi (Fraas)

Eoradiolites liratus (Conrad)
Praeradiolites maroni Douville
Cardium (Protocardium) cf. *hillanum* Sowerby
Pholadomya syriaca Conrad
P. vigneysi Lartet
"Diceras" noetlingi Blanckenhorn
Ampullina acuminata Whitfield
Turcica crispus Blanckenhorn
"Monodonta" antiqua Whitfield
Actaeonella salomonis Fraas
Tylostoma triplica Whitfield
Akera silicosa Whitfield
Acanthoceras rotomagense (Defrance)
A. cf. *cenomanense* (d'Archiac)

LATER CRETACEOUS FORMATIONS ON THE MARGINS OF THE RANGE

General statement.—The highest summits of the Lebanon Mountains are formed of rocks of Cenomanian age. The younger Cretaceous and Tertiary deposits occur only on the flanks of the range where strata of Turonian and Senonian age are recognized. There is no evidence indicating post-Senonian Cretaceous deposition in the Lebanon area.

Turonian deposits.—Deposits of Turonian age are rather irregularly developed along the coastal area in the region studied. Perhaps the best known section is that at Maameltein near Ghazir described by Zumoffen (1926, p. 128-131) and by Dubertret (1937b, p. 61-65). Here two horizons, distinguished both faunally and lithologically, are recognized. The lower, composed of hard, white siliceous limestones containing abundant large siliceous concretions and breaking with a conchoidal fracture, is characterized as the horizon of the ammonite *Thomasites rollandi* (Thomas and Peron). The upper horizon is composed of yellowish-white oölitic limestones below and sandy, soft limestones above. The oölitic strata contain a multitude of *Hippurites (Hippuritella) grossouvrei* Douvillé and *Durania laevis* Douvillé with a species of *Actaeonella;* the upper limestones are rich in echinoids including *Orthopsis zumoffeni* Cotteau, *Pyrina lamberti* de Loriol and *Echinobrissus ghaziriensis* de Loriol, and the gastropod *Nerinea pseudo-nobilis* Choffat. A similar series occurs south of Djouni.

On the eastern side of the Bekaa, the fault valley to the east of the Lebanon Mountains, a similar division into a lower zone of platy calcareous marl containing ammonites and an upper hippurite-bearing oölitic limestone has been recognized near Nebi Chit and south of Mejdel Anjar (Dubertret, 1937b, p. 67).

Senonian deposits.—Throughout its exposures the Senonian consists of thin-bedded white to yellowish-white shaly limestones, generally soft and chalky. At most places the formation is very sparingly fossiliferous. It is well exposed near Schweifat, and a long belt of this formation appears at a point just north of Saida (Sidon) and continues south beyond the southern limit of the Lebanon.

The best known exposure of the Senonian occurs at Sahil Alma, near Ghazir. The extensive Senonian fossil fish fauna is from this locality.

Hay (1903) lists 61 species from here. The few fossils other than fish reported from the Senonian include:

Terebratula cf. *carnea* Sowerby
Inoceramus cf. *cripsii* Mantell
Ostrea vesicularis Sowerby
Pseuderichthus cretaceus (Lewis)
Penaeus libanensis Brocchi
Protozoea hilgendorfii (Lewis)

Similar chalky marls of Senonian age occur in the Bekaa, particularly on the eastern side of the valley at the foot of the Anti-Lebanon Mountains.

TERTIARY FORMATIONS ON THE MARGINS OF THE RANGE

Eocene deposits.—The Eocene has not been found in place along the coastal area within the region studied. In the Bekaa, however, nummulitic Eocene limestones outcrop to form a series of low hills parallel to the western margin of the Anti-Lebanon Mountains. On the western side of the Bekaa, near Zahle, a brecciated limestone is almost wholly composed of *Nummulites gizehensis* Forskal. These beds are referred to the Upper Lutetian.

Miocene deposits.—The Miocene deposits of the coastal areas of the Lebanon have been well described by Keller (1933). Two small areas of marine Miocene occur on the coast within the area studied; none are known within the Bekaa. One area of outcrop is on the headland of Ras Beirut, in the city of Beirut. Here above a thin basal conglomerate a series of sandy clays, highly calcareous shales, and thick, soft, and porous limestones contains a rather large fauna, the most significant elements of which include:

Porites cf. *incrustans* Defrance
Solenastrea manipulata Reuss
Clypeaster zumoffeni de Loriol
Chlamys scabrellus (Lamarck)
Amussium cristatum (Bronn)
Venus multilamella Lamarck
Corbula gibba Olivi
Trochus patulus Brocchi
Fissurella italica Defrance
Haliotis volhynica Eichwald
Turritella subangulata Deshayes

The second outcrop area occurs between the headland at the mouth of the Nahr el Kelb and Djouni. Here a basal conglomerate with boulders of Cretaceous origin is overlain by a series of chalky, soft limestones containing great numbers of poorly preserved corals and calcareous algae. Other fossils include:

Clypeaster zumoffeni de Loriol
Chlamys scabrellus (Lamarck)
Pecten aduncus Eichwald
Spondylus crassicostatus Lamarck
Haliotis volhynica Eichwald

Pliocene deposits.—Marine Pliocene deposits occur in the north of the Republic of Lebanon near Lattakia and in the low hills beyond the northern end of the Lebanon Mountains. They are also known in Palestine near Mount Carmel, but have not been recognized in the area included in this report.

In the Bekaa, clays containing fresh-water fossils, including *Planorbis, Hydrobia, Limnea,* and *Paludina,* are intercalated with thin-bedded limestones and chocolate-colored shales with thin lignites. These are exposed near Schtaura, Zahlé, and at Kerak. Zumoffen (1926, p. 158-159) reports a thickness of between 150 and 200 meters for this series, which has been referred to the Pliocene by Blanckenhorn (1910, p. 437-439).

STRUCTURE

Structually the Lebanon Mountains are a horst. The fault on the western margin serves also to mark the eastern end of the Mediterranean Sea in that region, while that on the eastern side forms the western marginal boundary of the Bekaa, a long narrow graben which has been interpreted as a northern continuation of the Jordan Rift Valley, and possibly of the great African Rift zone.

In general the structural complications presented by the border fault along the Bekaa are much more simple than those on the coastal margin. In this latter area there is an extensive and very complicated fault zone that has greatly disturbed the entire marginal belt of strata. Vertical dips are common, and differential movement along the various faults has brought unrelated strata into contact with each other. The problem is further complicated because cultivation and terracing of the mountain slopes have reduced the amount of outcrop in critical areas. Considerable field work is necessary before all the facts required for a critical discussion of this area can be assembled.

In addition to these boundary faults there is a prominent transverse fault zone running east-west from the region of Beirut at least as far as Jebel Kenaise. This fault appears to be responsible for the development of the headland of Ras Beirut upon which the city of Beirut is located. Differential movement to the north and south of this fault has resulted in major differences in the distribution of the outcrops of the formations.

To the north, the main mass of the range is composed of essentially horizontal upfaulted strata (Fig. 3). The Jurassic strata outcrop along the lower elevations of the western side of the range, with the Cenomanian deposits forming the higher peaks, including (probably) Jebel Kenaise, as well as Jebel Sannin and Jebel Mneitri. To the south of the zone the section is further complicated by the presence of a longitudinal fault extending from a point north of Ain Zahalta to the southern limit of the area studied and paralleling the eastern marginal fault on the west. Between these two faults is a great mass of upfaulted Kimmeridgian limestones, while the long western slope of the range is formed of Cretaceous strata uplifted along the western marginal fault and dipping at low angles to the west away from the Jurassic outcrops.

Additional minor faulting and drag folding within the range present some stratigraphic complications, but the three longitudinal faults, plus the transverse fault discussed above, are the major structural elements responsible for the present development of the range.

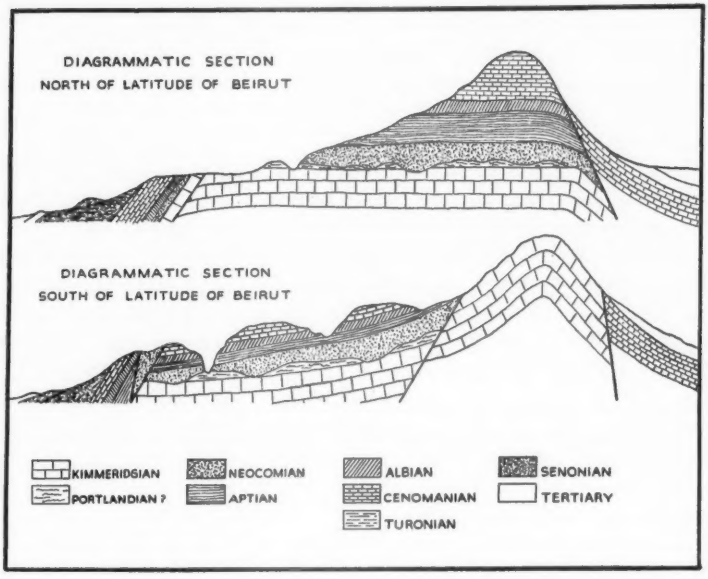


FIGURE 3.—*Diagrammatic sections across the Lebanon Mountains*
Sections north and south of the transverse fault.

AGE OF THE LEBANON UPLIFT

That the present elevation of the Lebanon area is a post-Pliocene development is apparent, if the clays and fresh-water limestones of the Bekaa area are correctly dated. Evidence suggests that the development of the Lebanon arch may have been initiated as early as post-Portlandian (?) and pre-Neocomian time. The deep channeling of the Jurassic deposits indicates extensive uplift, and the fact that the Neocomian continental deposits are thinner in the center of the range than on the flanks permits the suggestion that there may have been a low ridge in that area of the basin of deposition which is now occupied by the center of the range. Uplift in this area is also indicated by the presence of boulders of Cretaceous age in the basal conglomerates of the Miocene outcrops in the Beirut and Nahr-el-Kelb sections.

SUMMARY OF CONCLUSIONS

The main mass of the central area of the Lebanon Mountains is composed of Jurassic and Cretaceous deposits. The Jurassic deposits are referred to the Kimmeridgian and Portlandian (?), the Cretaceous to the Neocomian, Aptian, Albian, and Cenomanian. The Neocomian deposits are of continental origin, the others are marine.

Turonian and Senonian deposits occur on the flanks of the range, and local areas of nummulitic Eocene, marine Miocene, and freshwater Pliocene are present on the coast or in the valley of the Bekaa to the east.

Structurally the Lebanon Mountains are a horst bounded by longitudinal faults. The fault on the eastern side of the mountains forms the western margin of the graben valley of the Bekaa. This valley is a continuation of the Jordan Rift valley, and possibly of the African Rift valleys. A strong east-west transverse fault extends from the region of Beirut at least as far as Jebel Kenaise. To the north of this the strata lie essentially horizontal with the Jurassic outcropping on the lower slopes to the west and with the higher peaks formed of Cenomanian strata. To the south there is an upfaulted block of Jurassic forming the high eastern peaks, with the Cretaceous strata dipping gently off to the west.

The present uplift of the Lebanon Mountains is post-Pliocene, but there is some evidence that there was a tendency toward the formation of a positive structural area in this region as early as post-Portlandian (?) and pre-Neocomian time.

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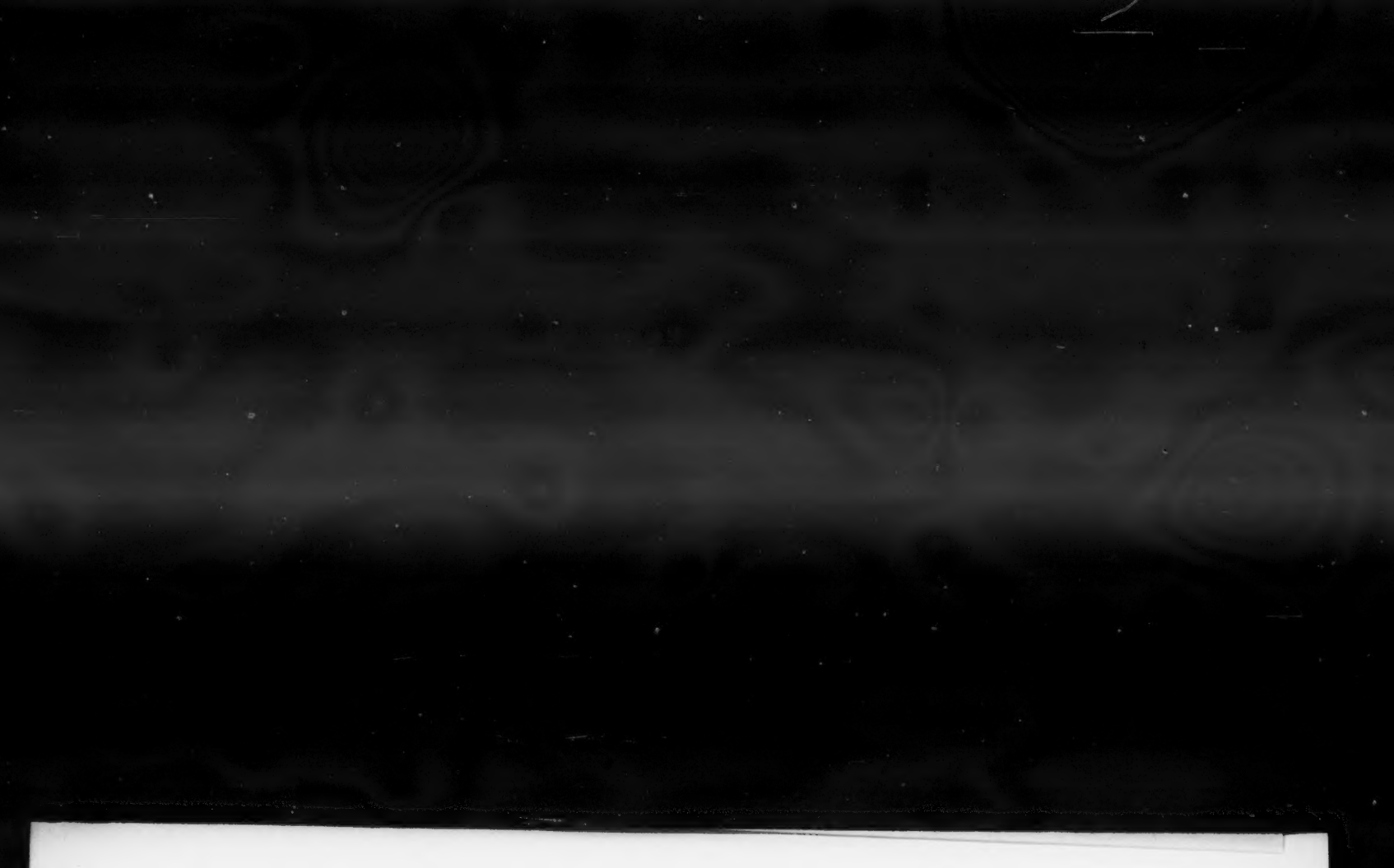

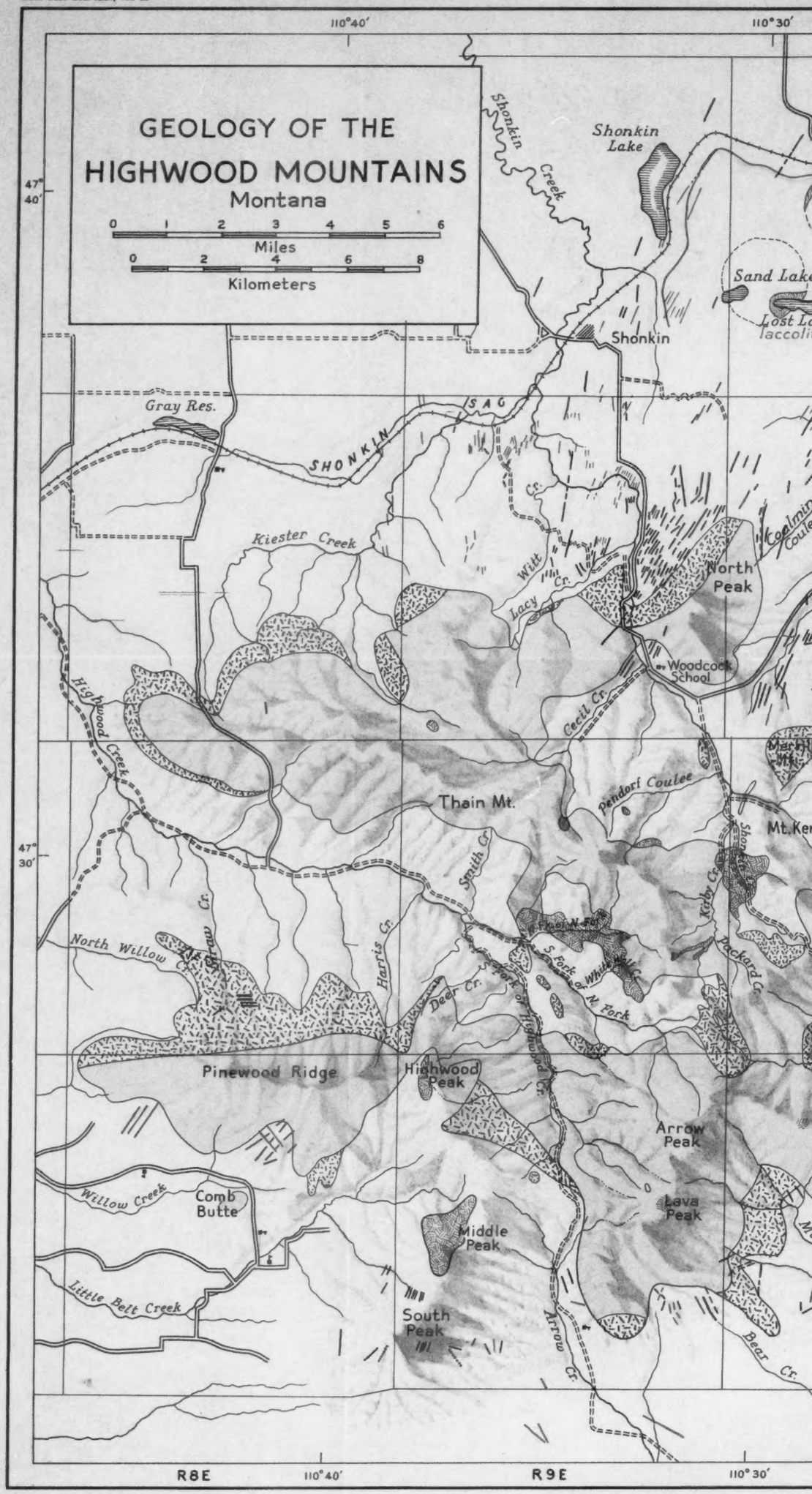

GEOLOGIC MAP OF THE

EXPLANATION

Al — Alnoite

Syenite porphyry (*intrusive*)

BP — Biotite phonolite (*intrusive*)

Augite mafic phonolite (*intrusive*)

Pseudoleucite mafic phonolite (*intrusive*)

Intrusive rocks stocks, laccoliths

Mafic phonolite (*extrusive*)

Amphibole phonolite (*intrusive*)

Quartz latite (*extrusive*)

Cretaceous rocks (*sandstones and shales*)

THE HIGHWOOD MOUNTAINS

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IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA

Part II. The Extrusive Rocks

BY E. S. LARSEN

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ABSTRACT OF PART II

Early eruptions of quartz latites, rather rich in potash, built up a volcanic mountain over 30 miles across on an irregular surface of late Cretaceous sediments. Erosion then removed much of the quartz latite. Renewed volcanism formed a

volcano made up of basaltic rocks (mafic phonolite) that covered the quartz latites. The phonolites vary in texture and in the kind and proportion of the felsic minerals present. All contain abundant phenocrysts of augite and some of olivine; some have phenocrysts of leucite, others analcime, and many have pseudoleucite. Some have phenocrysts of biotite and barium sanidine. The groundmasses contain about the same minerals as the phenocrysts with more felsic minerals and more biotite in the coarser-grained groundmasses.

INTRODUCTION

The extrusive rocks of the Highwood Mountains fall into two formations. The older formation is made up of clastic beds with some flows of uniform quartz latite that is characterized by phenocrysts of plagioclase, hornblende, and augite. These quartz latites are higher in K_2O than most quartz latites. They accumulated as a large volcanic pile that covered an area about the size of the present volcanic mountains. A long period of erosion with no evidence of volcanism followed the eruption of the quartz latites and reduced the volcanic mountains to remnants much like the present remnants of the mafic phonolites.

Following this interval of erosion, volcanism again became active, and the new extrusive rocks covered the hills and mountains of quartz latite and built up a new volcanic mountain. These later rocks are rather uniform dark basaltic rocks that carry as their chief minerals olivine, augite, orthoclase, nepheline, leucite, analcime, pseudoleucite, and biotite. They have about the composition of shonkinite and are called mafic phonolite.

No satisfactory base map of the area was available. The old topographic sheet on a scale of 1:250,000 was found very unsatisfactory. After about half the field work was completed a drainage map on a scale of half a mile to the inch, showing crest lines, was secured from the U. S. Forest Service for that part of the area which lies in the National Forest. After the field work was completed, Mr. Erwin Raisz prepared a map with plastic shading of the area from the Forest map, county maps, and other sources. The geology has been adjusted to this map as well as possible (Pl. 1). On this map the stocks and laccoliths are shown by a single pattern. Detailed descriptions and maps of these are given in the text.

Panoramas of the Highwood Mountains are shown in Plate 2.

ROCK CLASSIFICATION

The following discussion treats of the intrusive as well as extrusive rocks. In this report the rocks are classified according to Johannsen and, where analyses are available, according to the C. I. P. W. quantitative classification.

The rocks of the older group of volcanics all contain abundant plagioclase, a moderate amount of femags, and considerable quartz and orthoclase. They are quartz latites (226E) and differ greatly from all the later rocks. A small intrusive in the Highwood Peak stock is a nepheline-bearing (?) monzonite (2214).

The extrusive rocks of the later volcanic series nearly all contain from 40 to 55 per cent of femags. The chief rocks of the stocks and dikes have about the same femag content as do the sills and laccoliths that show no differentiation. The shonkinites of the differentiated laccoliths contain up to 75 per cent of femags and are therefore in classes 2 and 3 of Johannsen, many not far from the boundary between the two classes. The nepheline syenites of the laccoliths and the small amounts of nepheline syenite and related rocks of the stocks and dikes contain enough femags to place them in class 2.

Since plagioclase is rare in these rocks, nearly all fall in order 1 of Johannsen. Rare rocks fall in orders 2 and 3.

Quartz is rare in these igneous rocks; nearly all contain leucite, analcime, nepheline, or sodalite. The feldspar is sanidine. The ratio of foids to feloids depends chiefly on the extent to which the leucite and analcime have been replaced by sanidine and nepheline. Most of the lavas, a few of the dike rocks, and a few small bodies in the stocks contain unreplaced leucite and analcime; in these rocks orthoclase is subordinate to foids, and in rare local bodies in the stocks feldspar is lacking. These rocks therefore fall in family 21, rarely in family 25.

Some of the lavas, most of the dikes, nearly all the rocks of the stocks, and all those of the laccoliths contain feldspar in excess of altered nepheline and fall in family 17.

Most of the rocks are therefore classified in 2117, 3117, 2121, and 3121. A few rocks fall in 2125, 2113, and 219. The alnoite of Haystack Butte falls in 3125, and the monticellite peridotite in 411.

STRUCTURE

Reeves (1928) has discussed the structure of the Highwood Mountains region. He states (p. 165, 168):

"The Cretaceous formations . . . have a regional northeastward dip that is a continuation in a gradually decreasing amount of the tilt on the northeast flank of the Little Belt Mountains, which lie 15 to 20 miles south of the Highwood Mountains. In the southwestern part of the area mapped this dip commonly ranges from 1° to 2°, whereas in the northeastern part it averages about one-third of a degree, or approximately 30 feet to the mile. This northeastward dip persists to the Bearpaw Mountains, which are about 60 miles northeast of the Highwood Mountains.

"The northeastward dip of the strata in the plains around the Highwood Mountains persists without marked modification in the mountains. . . . Although no attempt was made to map in detail the structure of the mountain area, the brief field work done showed that although the formations underlying the volcanic rocks

are locally faulted and tilted by intrusive bodies, the mountain area is not domed like the other mountain groups of the region and has not subsided like the Bearpaw Mountains. As far as could be determined the faulting in the Highwood Mountains is all of the normal type, and the tilting observed was probably that accompanying normal faulting and intrusive activity.

". . . In the plains around the Highwood Mountains the regional northeastward dip of the strata is interrupted by normal and thrust faulting. . . . From the observations made the writer is of the opinion that the thrust faulting adjacent to the Highwood Mountains occurs only in the area lying northeast of a northwest-southeast line drawn through the center of the mountains."

The authors of this paper did not make a careful study of the structure which was made difficult by the very poor base map, the lack of good bedding or horizon markers in most of the volcanic rocks, the irregular erosional surfaces at the base of the mafic phonolite, and the metamorphism and alteration of the sedimentary rocks in the central mountain area. The writers' observations confirm the statements of Reeves that in general the rocks in the mountain area are nearly flat but are locally faulted and tilted.

The isolated body of volcanic rocks of Jensen Mountain, south of Alder Creek, is faulted on the southeast side and tilted to the southeast. Dips of from 20° to 35° were measured on the well-bedded latite conglomerate. For a distance of 100 yards from the fault the volcanic rocks are bent and dip away from the fault. The isolated body of volcanic rocks just north of Alder Creek is probably bounded by a fault on its southeast side.

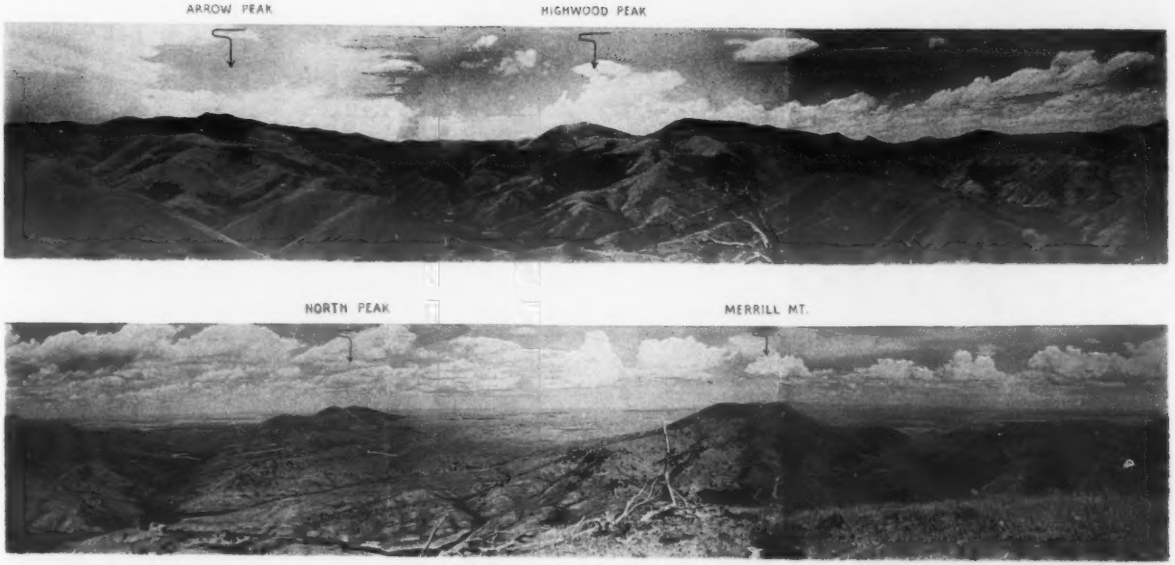
A few miles to the north and southeast of North Peak the sediments over a large area are intruded by many sills and dip steeply to the southeast. This whole eastern slope of the mountains appears to have been faulted and locally tilted.

In the southeastern part of the mountains there appears to be a good deal of undulation in the volcanic rocks, and especially in the quartz latite, which locally has well-bedded tuff. On the southeast slopes of East Peak near the base of the mountain the sediments and volcanic tuffs dip into the mountain. Dips of 38° NE. and 38° NW. were observed. In a section up Davis Creek, to the west of East Peak, several good dips in the latite tuff were observed; at an elevation of 5450 N. 30° W., 22° SW.; at 5500 N.-S., 35° W.; and at 6150 N. 45° E., 30° NW.

QUARTZ LATITE

DISTRIBUTION AND THICKNESS

The quartz latites are the oldest volcanic rocks exposed in the Highwood Mountains, except for the rhyolitic ash (bentonite) in the Cretaceous. They overlie an irregular erosional surface cut in the Cretaceous rocks and are overlain on a similar irregular erosional surface by the mafic phonolites. The lowest exposures of the latites are only a few



PANORAMA OF THE HIGHWOOD MOUNTAINS

Taken from Mt. Kennon. 250°–270°.

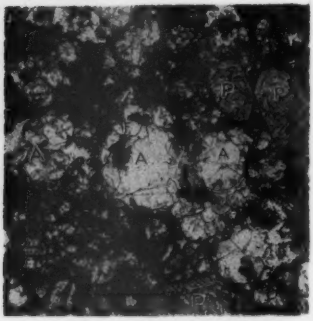


FIGURE 1. SHOWS CUSPS OF ORTHOCLASE EATING INTO THE ANALCIME (FBH L 109)
Ordinary light.

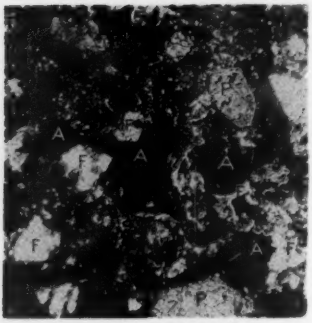


FIGURE 2. AS FIGURE 1
Crossed nicols.

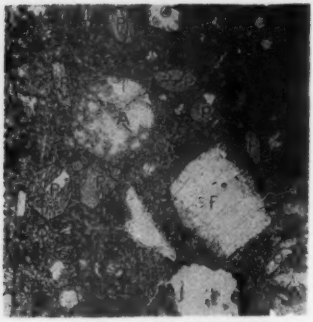


FIGURE 3. CLEAR ANALCIME CLOUDED NEAR BORDERS (FBH 114)
Ordinary light.

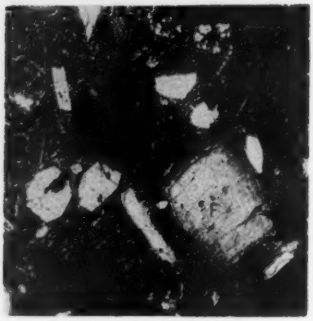


FIGURE 4. AS FIGURE 3
Crossed nicols.

PHOTOMICROGRAPHS OF MAFIC ANALCIME PHONOLITES
A = analcime, P = pyroxene, F = zoned sanidine. x 15.

hundred feet above the general level of the Great Plains, and the highest exposures of the Cretaceous are nearly 4000 feet above this level. While a part of this elevation may be due to doming and other structures developed during the volcanic activity, much of it represents the original relief of the surfaces over which the lavas were extruded. At the time of the latite eruptions the region must have been a group of hills or the flanks of a larger mountain range to the south and west. The relief in the area was at least 3000 feet.

The area over which the latites are distributed is about the same as that of the mafic phonolites—about 30 miles in the maximum dimension. Only remnants of the latites now remain, and the maximum exposed thickness is about 1000 feet, but they must originally have formed a larger and much thicker pile. No centers of eruption for the latite were found, and only a very few small intrusives.

GENERAL HARACTER

The latites are made up of tuffs, breccias, lava flows, and some conglomerates. Lava flows probably make up a somewhat smaller amount of the latite than do tuff and breccia. Lava flows are especially prominent in the northwestern part of the mountains, while tuff makes up most of the formation in the southern part. Conglomerates are usually found chiefly on the flanks of a volcanic pile, but the conglomerate of the latite is best developed in the drainage of Kirby Creek, the west fork of Shonkin Creek, north of Prospect Peak, not far from the center of the latite outcrops, where conglomerate attains a thickness of several hundred feet. This conglomerate is made up of well-rounded fragments, mostly of the typical latite but some of limestone and other rocks. It is well bedded and contains some poorly preserved plant remains. It rests on the Cretaceous where the base of the latite is at a relatively high elevation.

The beds of tuff and breccia are commonly rather thick; the fragments in any bed are usually of one kind of latite. They are fairly well indurated, and some of the harder fine tuffs are difficult to distinguish from the flows.

The flows are mostly less than 100 feet thick. They are interbedded with the tuffs and seem to be as flat and well layered as the tuffs.

The latite gives better exposures and steeper slopes than the softer sedimentary rocks but more broken and less regular than the cliffs of the phonolites. In general, the outcrops are lighter colored than those of the phonolites. However, with the relatively poor exposures, deep weathering, and abundant vegetation of the area, it is rarely possible to distinguish between the latites and phonolites from a distance.

PETROGRAPHY

The latites are an unusually uniform group of lavas. They vary from very light gray to red brown or darker gray, rarely dark gray. Their most characteristic feature is the presence of hornblende phenocrysts which can be easily found in most hand specimens and commonly are rather conspicuous. Most of the rocks show white, millimeter-sized, stout plagioclase tablets and a little biotite in an aphanitic groundmass.

Under the microscope nearly all the rocks show phenocrysts of feldspar and hornblende with more or less of biotite and augite, in a groundmass that contains a variable amount of small oligoclase tablets, pyroxene, and iron ore in a submicroscopic to very fine matrix that is of the type common to many quartz latites and very probably is made up chiefly of alkalic feldspar and quartz. Most of the rocks are seriate porphyritic, the phenocrysts nearly all less than 2 millimeters long. The rocks are all considerably altered, and the feldspars are particularly cloudy from alteration.

The feldspar phenocrysts show strong oscillatory zoning and complex twinning. They vary somewhat, averaging calcic andesine in some specimens and oligoclase-andesine in others. In one specimen the core is An_{51}, the main part An_{30}, and a narrow outer zone An_{20}. The feldspar is considerably altered, and some of the variation may be due to alteration.

The hornblende is always more or less resorbed; in some specimens this is revealed only by the irregular shape of the hornblende grains and by a narrow border of iron oxide; in others they are almost or completely gone, and their place is taken by an aggregate of iron ore, feldspar, and pyroxene. Pyroxene is abundant in the replaced hornblende chiefly where the resorption is complete. The hornblende is in part green to olive green, in part chestnut brown basaltic. Both types show zoning. The common green hornblende is derived from the basaltic hornblende, and all stages in the replacement can be seen from a narrow border of the green about the brown to a "sea and island" texture in which only small specks of the brown remain. May of the thin sections show only one kind of hornblende, but in most of these the hornblende concentrated from the powdered rock shows both varieties. In one specimen the hornblende has been replaced by pyroxene and biotite. The central part of the hornblende is replaced by an aggregate of biotite plates; about this is a narrow rim of biotite oriented with the original hornblende, and beyond is an irregular border of magnetite and augite grains.

A little of the pyroxene is in large phenocrysts, but much of it is in smaller irregular grains. In a few specimens the large augite crystals have a narrow, irregular corona of hornblende which has suffered the usual resorption. The biotite has suffered nearly as much magmatic resorption as the hornblende.

The history of the crystallization of the rocks appears to have been about as follows. While the magma was in a deep reservoir, pyroxene was one of the first minerals to begin crystallization. It precipitated only in small amount and then ceased to be in equilibrium with the melt, and basaltic hornblende came out in rather large amount, partly as separate phenocrysts and partly replacing and growing about the pyroxene. Biotite and plagioclase were also crystallizing. The magma was then probably moved to a higher level and lost some of its mineralizers so that hornblende and biotite were no longer stable and were resorbed while pyroxene was being precipitated as small grains at some distance from the hornblende. This resorption was rarely carried to completion, possibly because the magma was erupted

before that stage was reached. After the magma spread over the surface the remaining liquid crystallized as the groundmass. The replacement of the basaltic hornblende by the green hornblende took place late in the sequence and probably after eruption as a paulopost product.

Near the stock of Highwood Peak the quartz latite has been hydrothermally altered. Considerable secondary light-colored uralitic hornblende has been introduced in fractures and replacing the pyroxene. In one specimen, diopside and biotite have also been introduced, and along narrow veinlets tiny grains of a colorless mineral with a high index of refraction and rather strong birefringence.

Only one specimen shows any similarity to the overlying phonolites. This is a light-colored dense rock with conspicuous phenocrysts of hornblende and none of feldspar but with irregular patches of clear analcime ($n = 1.488$). In the hand specimen it looks like a typical latite, lighter-colored than average. It was collected about 2 miles southwest of Stillwell Peak and west of Timber Creek, from near the base of the latite. In thin section this rock has much olive-green hornblende, somewhat resorbed, and some green, strongly zoned pyroxene, which resembles that of the phonolites; also recognizable are light-colored patches, some of which look like phenocrysts, of analcime, and abundant phenocrysts of apatite. The groundmass is made up of fluidal laths of alkalic feldspar, and augite rods.

CHEMICAL ANALYSES

In column 1 of Table 1, an analysis by E. B. Hurlburt and B. Barnes is quoted from Pirsson (1905, p. 164) and compared with Daly's averages for quartz latite and trachyandesite. It seems probable that Pirsson's analysis was one of the more andesitic varieties, but the quartz latite is fairly uniform, and the analysis checks well with estimates made from thin sections, hence it may be taken as representative. No specimen of these rocks is considered to be fresh enough to justify a new analysis. The modes were not measured on the analysed specimens but on two specimens of typical latite.

MAFIC PHONOLITES

NAME AND DISTRIBUTION

Pirsson (1905, p. 166) has called these lavas analcime-leucite basalt, but, since plagioclase is entirely absent from the typical basaltic lavas in the Highwood Mountains and barium sanidine (hyalophane) is characteristic, the name jumillite is more appropriate. Jumillite was proposed Cámara by Osann (1906, Cámara, 1935a; 1935b) as a name for the leucitic lavas from Jumilla, Spain, which are characterized by pyroxene, olivine, barium-bearing sanidine, biotite, leucite (altered to analcime), and hornblende. Jumillite would therefore be the effusive equivalent of leucite shonkinite, and Tröger (1935, p. 21) places jumillite as an effusive in the family of shonkinites. In the analcime jumillites, analcime takes the place of leucite. In the interest of a simple, easily understood nomenclature, these rocks are here called mafic phonolites or mafic leucite phono-

lites. In Johannsen's classification they fall in (2121E) and (3121E), and the rocks with pseudoleucite or lacking leucite and analcime in (2117E) and (3117E).

TABLE 1. *Analyses, norms, and modes of quartz latite*

	1	2	3
	Quartz latite	Average quartz latite	Average trachy-andesite
ANALYSES			
SiO_2	59.24	62.43	57.84
TiO_2	.22	.85	1.11
Al_2O_3	13.84	16.15	17.24
Fe_2O_3	5.46	4.04	3.97
FeO	1.36	1.20	3.18
MnO	tr	.09	.05
MgO	4.79	1.74	1.25
CaO	5.60	4.24	4.20
Na_2O	3.13	3.34	5.67
K_2O	4.22	3.75	3.63
H_2O+	2.02	1.90	1.30
P_2O_5	.34	.27	.57
$SO_3(+S)$	.08	.....	.....
Cl	.04	.....	.....
BaO	tr	.....	.....
	100.34		
NORMS			
Q	10.2	18.2	2.8
or	24.5	21.7	21.1
ab	26.2	28.30	48.2
an	11.1	18.3	10.8
di	11.4	.7	5.1
hy	6.7	4.1	1.3
mt	3.6	1.9	5.8
il	.5	1.5	2.1
ht	2.9	2.7	
ap	.7	.7	1.3
Rest	2.1	1.9	1.3
Position	II.4.2.3	I(II).4.'3.3'	'II.5.2.4
MODES			
Phenocrysts	vol.	wt.	
Andesine	15	14	
Hornblende	15	18	
Biotite	½	½	
Ores	2	4	
Groundmass	68	64	

Mafic phonolites and related rocks constitute most of the higher parts of the Highwood Mountains. They form the ridges on both sides of, and around the head of, Highwood Creek, and arms extend from these ridges to the northeast to North Peak, to the east to Stillwell Peak, and to the southeast to East and Lava peaks. The length is about 30 miles northwesterly; the width is somewhat less. Their maximum thickness is

about 2000 feet. The original volcanic pile was somewhat larger areally, and considerably thicker.

THE LOWER CONTACT

The base of the mafic phonolites is much higher in the central part of the mass, near the head of Highwood Creek, than near the margins. In many places near the margins it reaches an elevation about 500 feet above the general elevation of the Great Plains, while in the central part it is 1500 to 3000 feet above. It rests upon either the Cretaceous sediments or the quartz latites. In addition to the great elevation of the base in the central area, rapid local changes—some over 1000 feet—take place. This irregularity at the base of the phonolite is believed to reflect chiefly the irregular surface over which the rocks were spread; most of the local irregularities are certainly due to this. However, some of the irregularity may be due to doming and faulting or other post-extrusive structures. Exposures are generally poor in the central area, and the topographic map is very poor; hence no attempt has been made to work out the structure. Steep dips were seen locally, in part associated with the stocks.

Before the eruption of the mafic phonolites the quartz latites had been largely removed by erosion—to an even greater extent than the phonolites have been removed since their eruption—indicating a fairly long time interval between the two periods of eruption.

GENERAL CHARACTER

The phonolites underlie many of the steep slopes but they are not very well exposed. Outcrops are dark gray to reddish. The material is divided about equally between flows and clastic rock. The flows are for the most part between 10 and 50 feet thick; there are probably some sills. The clastic material is chiefly breccia with fragments up to a foot or more across. Most of it is poorly sorted and bedded with some finer tuff.

The rock of many of the thick flows is dense, dark green, and appears fresh, while that of the thin flows and especially of the breccias tends to be highly vesicular, reddish brown, rich in zeolites, and altered.

These rocks show little variety in the hand specimen. Most of them are nearly black but they are red brown where the iron has been oxidized; some are rather light gray. A few are dense, but most are vesicular, and the vesicles have been more or less filled with zeolites. Zeolites occur in unusually large amounts, and irregular masses weighing over 100 pounds were found. Most of the rocks show abundant and prominent prisms of augite commonly 2 to 4 millimeters long and some olivine in somewhat smaller grains, amber yellow where fresh but commonly more or less altered to red-brown iddingsite or limonite. They frequently show

abundant rounded millimeter crystals of leucite, analcime, or their alteration products. A few carry inconspicuous tablets of glassy feldspar. The pyroxene prisms are more or less oriented in most of the rocks and in some they have a very good linear parallelism.

MICROSCOPIC PETROGRAPHY

General.—Under the microscope the greater part of the rocks are much alike except that some have clear, primary analcime as the chief felsic mineral, and others have a cloudy secondary analcime or other zeolite; a few have leucite; and some have the leucite or analcime more or less completely replaced by a mixture of feldspar and secondary analcime (?). No rock with both primary analcime and fresh leucite has been found. The groundmass also shows some variation. Rare rocks approach trachyte or phonolite on the one side or a pyroxene-rich rock on the other.

Nearly all the rocks are distinctly porphyritic; the phenocrysts in most specimens make up about half the rock. They vary in size, and in some specimens the analcime or leucite, and to a less extent the other phenocrysts, grade down to the crystals in the groundmass, giving the rock a typical seriate porphyritic texture. Augite phenocrysts make up about a fifth of the rock. They occasionally have irregular inclusions of the groundmass and they are zoned and commonly show several oscillatory zones. Most of the cores are nearly colorless; the outer zones are pale green. The green variety has a somewhat higher index of refraction, larger extinction angle, and weaker birefringence. The optical properties are given in the section on mineralogy. The olivine phenocrysts show little or no resorption. Except for some alteration to iddingsite they are fairly fresh in the rocks with fresh clear analcime; in the rocks with cloudy analcime they are commonly largely or completely altered to iddingsite, or less often to iron oxide or serpentine. They have about 12 to 25 weight per cent of fayalite as shown by the optical properties. Biotite, much resorbed, is a sparse phenocryst in a very few of the rocks. A few of the rocks carry small tabular phenocrysts of barium sanidine.

The groundmass of the lavas is rather variable in amount but in most specimens forms about half the rock. It is made up of about the same minerals as the phenocrysts. It is mostly analcime, more altered than that of the phenocrysts, small rods of augite, more or less olivine, mostly altered, magnetite, apatite, and a variable amount of feldspar. In most specimens the feldspar is in small tablets, in some it is in irregular patches that mold about or enclose the other constituents. In the latter type it partly replaces the analcime and in some of the rocks shows zoning.

The feldspar of the groundmass is optically like the phenocrysts. Andesine with albite twins is very rare. The rocks in which the leucite or analcime has been replaced by feldspar have groundmasses that tend to be fine granular feldspar with a variable amount of analcime. This feldspar is chiefly sanidine in some rocks and hyalophane in others.

The cavities of the rocks commonly have one or more zeolites—analcime, natrolite, or thomsonite—with rare calcite. Secondary products in some of the rocks are sericite, chlorite, serpentine, and iron oxide.

For detailed description the rocks have been divided into eight types which are in large part gradational. Out of 85 thin sections examined the types and the number of sections belonging to each type follow:

mafic leucite phonolite	with fresh leucite	4
mafic analcime phonolite	with clear analcime	20
	with cloudy analcime	24
	with analcime altered to natrolite and other zeolites	8
mafic pseudoleucite phonolite	with pseudoanalcime or leucite, now mostly sanidine and analcime	16
	with fine-grained groundmass made up mostly of feldspar	6
mafic phonolites	without phenocrysts of analcime or leucite	3
miscellaneous basaltic rocks	without olivine, leucite or analcime	4

In selecting rocks for thin sections the fresher rocks were preferred; thus the rocks with cloudy analcime and other zeolites make up a considerably larger proportion of the mass than the list indicates. About 20 specimens with fresh leucite or analcime were examined in powder, and leucite and clear analcime were found in about the same proportion as in the thin sections. The clear analcime and leucite can be distinguished from each other only by the twinning of the leucite, possibly by the cleavage of the analcime, or by measuring the index of refraction. In every specimen the identity of these minerals was checked by an index of refraction measurement. In no specimen were the two minerals found together.

No one type of rock appears to be especially abundant in one part of the mountains or near one horizon in the section. The leucite rocks were mostly in rather thick flows. They were found more abundantly in the northeastern, eastern, and southern parts of the mountains than in the central and western parts, but this was probably due to imperfect sampling.

Mafic analcime phonolite.—The phonolites with clear analcime are widespread and are the most abundant of the fresh rocks. They are dark to medium dark gray or greenish gray and are rather dense. They are fresh-looking, and the analcime tends to be inconspicuous. Although augite and olivine are abundant phenocrysts in all the rocks, analcime is the chief phenocryst, but in a few it is present in only small amounts. It tends to collect about the augite or feldspar phenocrysts, in

some cases like a string of beads. In the freshest specimens it is clear and glassy, has a uniform index of refraction (1.493) somewhat higher than that of common analcime, and contains considerable K_2O. In nearly all the rocks it is more or less altered along the margins of the crystals and along fracture to cloudy analcime, which appears to be ordinary analcime, as judged from the lower index of refraction. As this alteration becomes more complete these rocks grade into cloudy analcime phonolites, and with this alteration the olivine is more altered. In some specimens the analcime is in fairly well-bounded crystals, but it is commonly serrated or ragged from reaction to feldspar; in some specimens feldspar eats into it in rounded cusps or cuts it in thin, arclike veinlets that isolate a part of the crystal (Pl. 3, figs. 1, 2).

Feldspar phenocrysts are present in small amount in some of the rocks. They are clear tablets up to a millimeter in largest dimension, show Carlsbad twins, and look like sanidine but have a β index of refraction about like that of Canada balsam. They are commonly zoned with several narrow oscillatory zones. An analysis shows the mineral to be barium sanidine.

The groundmass of most of these rocks is rather fine analcime and barium sanidine, with more or less iron oxide and pyroxene. In three-quarters of the specimens the groundmass feldspar is in tablets; in the other quarter it is in irregular patches molding about the other constituents and is strongly zoned. In some of the rocks the groundmass is made up of feldspar laths imbedded in cloudy analcime and other zeolites, probably derived from nepheline. In one specimen the analcime phenocrysts are present in small amount and are much resorbed; the groundmass greatly predominates and is made up largely of coarse laths of barium sanidine with little interstitial analcime. The amount of mafic minerals in the groundmass of the rocks varies greatly. The amount of groundmass varies from much over half the rock to much less than half.

Photomicrographs of a typical specimen of the phonolite (Pl. 3, figs. 3, 4) show phenocrysts of analcime clouded on the borders and along fractures. The rock shows a large, zoned crystal of barium sanidine. An analysis, norm, and mode of this specimen (FBH L114) are shown in Table 2, column 6, and an analysis of the barium sanidine will appear in a later section on mineralogy. The specimen came from the cliffs at the base of the mafic phonolite 1½ miles N. 60° W. of Comb Butte.

Photomicrographs of a specimen (FBH 500) (Pl. 4, figs. 1, 2) show clear analcime replaced irregularly along the borders by very fine-textured pseudoleucite. The groundmass has barium sanidine laths in a very fine matrix.

An analysis norm, and mode of a fresh analcime phonolite (FBH 169) from a flow on the west end of the ridge which is east of the Geyser-Geraldine road and west of Palisade (Round) Butte, are shown in column 1 of Table 2. An analysis of the clear analcime phenocrysts from this rock is given in the section on mineralogy. This rock shows the usual phenocrysts, but the groundmass is made up of rather coarse feldspar molding between the other constituents with some mafic minerals. The feldspar replaces the analcime in cusps (Pl. 3, figs. 1, 2). The feldspar is strongly zoned in the larger patches. The cores have $\alpha > 1.540$, and in contact with the analcime $\gamma < 1.540$, indicating cores of barium sanidine rather rich in barium grading to borders of ordinary sanidine. A similar interstitial feldspar is described in detail in the section on mineralogy.

Mafic leucite phonolite.—The rocks with fresh leucite were found only in fairly thick, fresh, massive flows and in several places were associated with irregular or sill-like intrusives of a granular rock rich in fresh leucite. Specimens were col-

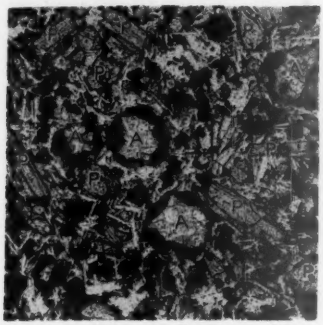


FIGURE 1. ANALCIME REPLACED ALONG BORDERS BY FINE-TEXTURED PSEUDOLEUCITE
Ground-mass made up of laths of barium sanidine and very fine material (FBH 500). Ordinary light.

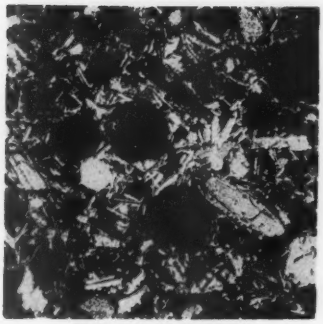


FIGURE 2. AS FIGURE 1
Crossed nicols.

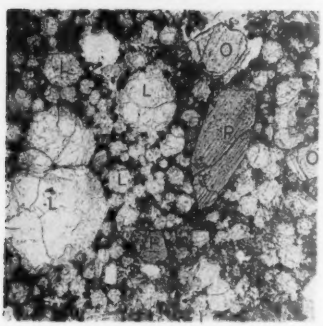


FIGURE 3. ROCK WITH LARGE AND SMALL LEUCITES (FBH L 290)
Large leucites replaced by pseudoleucite a very little on borders; small leucite more replaced. Ordinary light.

FIGURE 4. ROCK WITH LEUCITE EMBAYED ALONG MARGINS BY PSEUDOLEUCITE (F.B.H. 210). Ordinary light.

PHOTOMICROGRAPHS OF MAFIC PHONOLITES
A = analcime, L = leucite, O = olivine, P = pyroxene. x 15.

FIGURE 1. PSEUDOLEUCITE MERGES WITH GROUNDMASS (FBH L 666)
Ordinary light.

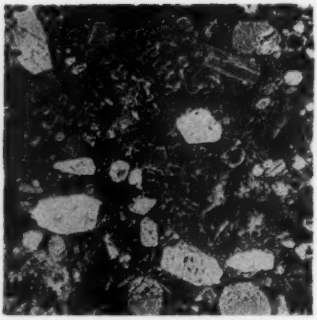


FIGURE 2. AS FIGURE 1
Crossed nicols.

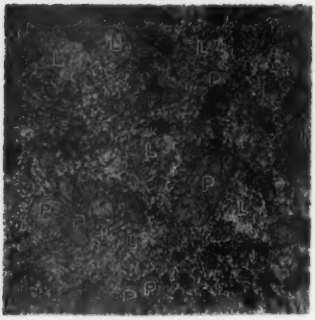


FIGURE 3. PSEUDOLEUCITE LIKE GROUNDMASS EXCEPT FOR LACK OF FEMIC MINERALS (FBH L 668)
Ordinary light.

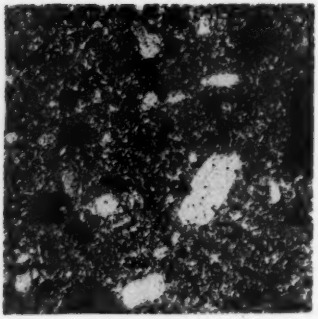


FIGURE 4. AS FIGURE 3
Crossed nicols.

PHOTOMICROGRAPHS OF MAFIC PSEUDOLEUCITE PHONOLITES
L = pseudoleucite, P = pyroxene. x 15.

lected from (1) the west slope of North Peak, (2) the ridge east of Timber Creek (a north fork of Cottonwood Creek) about half a mile above the Forest Boundary, (3) the hill south of the main ridge which is east of the Geraldine-Geyser road and west of Palisade Butte, (4) on Pine Ridge, and (5) in the main gulch in the ridge south of Lava Peak about 200 feet above the base of the volcanics.

In the hand specimen the leucite phonolite looks like the clear analcime phonolite. It is dark greenish gray, has the usual phenocrysts, and the leucite is greenish and inconspicuous. In thin section also the two rocks look very much alike. The olivine shows very little alteration to iddingsite. The leucite occupies the same position as the analcime of the analcime rocks and alters to cloudy analcime much as the clear analcime does. The index of refraction of the leucite is normal (1.507). In all the specimens the leucite shows some replacement by cloudy analcime. In one specimen the leucite shows slight replacement by feldspar on the borders. The groundmass is fine-grained and made up of much pyroxene and has abundant feldspar in irregular patches and intergrowths with analcime. In another rock the replacement has gone further, and lacework intergrowths of feldspar and analcime that look much like the myrmekite replacement in feldspar project into the leucite crystals. The groundmass here is much coarser than in the rock just described and is made up of irregular to stout tabular feldspar crystals, rather coarse intergrowths of feldspar and analcime (possibly derived from leucite), and some pyroxene.

In a specimen of leucite phonolite with abundant fresh leucite of variable sizes (Pl. 4, fig. 3) (FBH 560) the large leucites are little replaced by feldspar, but the smaller ones show more replacement. The groundmass contains biotite, pyroxene, and iron ore.

In a specimen (FBH 210) with the leucite partly replaced about the margins by a very fine-textured pseudoleucite (Pl. 4, fig. 4) the replacement forms embayments. In a third specimen the leucite is more replaced by the lacework of feldspar and analcime, and the groundmass is intermediate in coarseness and is made up of a fine intergrowth of the feldspar and cloudy analcime with some mafic minerals.

The leucite phonolites lack the tabular feldspar of the analcime phonolites but have more feldspar in the groundmass than most of the analcime rocks. The feldspar is commonly zoned, and its indices of refraction for α vary from a little above 1.540 to about 1.530, indicating a barium sanidine grading from about 22 per cent of celsian to sanidine with little celsian. The sanidine replacing the leucite has little celsian.

Four small sill-like or less regular intrusives of a rock much like the leucite phonolite but with coarser groundmass have been found in the volcanic rocks, and more are probably present as they are not easy to recognize in the field.

Their localities are:

(1) South slope of North Peak above the Woodcock school house and half way up the mountain.

(2) On the western slope of the first peak west of Pinewood Peak. Two conspicuous columns—10 to 15 feet high in the dense woods.

(3) Half way up the western slope of Lava Peak.

(4) Cottonwood Creek; 1 mile above the boundary of the National Forest.

These rocks are much like the leucite phonolites except that they lack a fine groundmass but have a little barium sanidine molding between and about the leucite and other constituents.

A specimen from the west slope of North Peak has been analyzed (FB 247) (Table 2, column 3). This rock contains a more definite groundmass than some of

these intrusives and is made up chiefly of pyroxene rods up to 2 mm. long, olivine in somewhat smaller grains, and leucite mostly between ½ and 1 millimeter across. The groundmass comprises only a small part of the rock and is made up of pyroxene, olivine, leucite (?), and zeolites imbedded in coarser irregular crystals of feldspar. The olivine is but little altered to iddingsite; the leucite is altered along the borders and along fractures to cloudy analcime but appears to be for the most part fresh. It is replaced a little along the borders by sanidine. The groundmass leucites are much altered to cloudy analcime; there may have been a little nepheline now altered to zeolites. The feldspar is clear and glassy. It is strongly zoned with cores of barium sanidine with over 42 per cent celsian; the cores grade in broad zones to borders of sanidine with little celsian. The feldspar replacing the leucite contains little celsian. This feldspar is described in more detail in the section on mineralogy.

The low potash and high H_2O in the analysis indicate much more alteration of the leucite than was estimated from the thin section. A calculation of the mineral composition from the chemical analysis indicates that the rock has about 20 per cent leucite and 20 per cent zeolites by weight.

Mafic phonolite with cloudy analcime or zeolites.—Rocks with cloudy secondary analcime and little or no clear analcime are considerably more abundant than those with clear analcime. In the hand specimen the two rocks are very much alike. However, the cloudy analcime rocks are red brown and look more altered; they are more vesicular and carry more zeolites; and their analcime is dull white instead of vitreous and inconspicuous. In the thin section, too, the two rocks are much alike except that the cloudy analcime rocks are more altered. Their olivine is commonly completely altered to iddingsite, iron oxide, or serpentine; the analcime is clouded, has an index of refraction of 1.488, and shows fractures that look like shrinkage cracks. Some secondary natrolite is associated with the claudy analcime, and in a few specimens only natrolite is present. The groundmass of these rocks is chiefly of the type with tabular feldspar, and many of the rocks have small phenocrysts of tabular barium sanidine. In only 10 per cent of the thin sections examined was the groundmass of the type with feldspar molding between and around the other constituents. The zeolites (analcime and natrolite) are more abundant in the cavities of these rocks than they are in the clear analcime rocks.

The rocks in which the analcime is replaced by natrolite are much like the analcime rocks except that the olivine is altered to iron oxide or serpentine and the rocks contain much natrolite throughout. They are mostly red from oxidation of the iron. In one such rock with much natrolite, the only feldspar in the groundmass is sanidine ($\alpha = 1.519$, $\gamma = 1.527$). In some specimens the natrolite replacing several analcime phenocrysts extinguishes as a unit.

Mafic phonolite with pseudoleucite.—In about 22 per cent of the thin sections examined, the leucite or analcime is more or less completely replaced by sanidine and cloudy analcime. All stages of replacement are found, from slight replacement along the edges, to complete replacement with the original form preserved, to a merging of the pseudoleucite into the groundmass. In the hand specimen these rocks are much like the phonolites with clear analcime. In some, the form of analcime (or leucite) cannot be seen with a pocket lens; in others it is white and conspicuous.

The rocks carry the same phenocrysts and have the same types of groundmass as were found in the analcime and leucite phonolites. In the specimens in which the

replacement of the leucite or analcime has been more extreme the groundmass is coarser and more granular.

In these rocks the olivine tends to be a little more altered to iddingsite than in the leucite and analcime phonolites, and in some specimens the pyroxene has ragged borders. In the early stages of replacement, the leucite or analcime phenocrysts are replaced along the borders or in patches by feldspar and cloudy analcime. The feldspar is chiefly in a lacework intergrowth with analcime that resembles myrmekite. As the replacement goes to completion, the feldspar tends to be coarser, and the cloudy analcime tends to concentrate near the centers of the grains. In some specimens the feldspar is in plumose or rudely radiating aggregates. The final stage of replacement is to a granular aggregate of feldspar with some analcime.

Most of these rocks contain the same groundmass feldspar (zoned barium sanidine) as the leucite and analcime phonolites, and the common feldspar in the replaced analcime (or leucite) is sanidine with only traces of barium.

In the final stage of replacement the rocks are phonolites with abundant phenocrysts of olivine and augite and with analcime in place of nepheline. They have much the same composition as the analcime phonolites but contain more water.

Mafic phonolite with leucite or analcime replaced by feldspar.—About 7 per cent of the specimens collected have a gray to nearly white fine-grained groundmass. In one specimen, large rounded white patches are pseudoleucite (or analcime), but in many no evidence of leucite or analcime remains.

In thin section these rocks have less cloudy analcime than the ordinary pseudoleucite rocks; they contain more biotite, and two out of five specimens contain some andesine with Carlsbad, albite, and pericline twins.

The groundmass in most specimens is fine granular and is made up chiefly of equant or stout tablets of sanidine ($\alpha = 1.520$, $\gamma = 1.528$), more or less andesine or labradorite, some analcime, biotite, and iron oxide. The leucite (?) phenocrysts are replaced by a similar mixture lacking the dark minerals. In some specimens the pseudoleucite phenocrysts are not easily recognizable with the microscope, but with a pocket lens in the thin section or hand specimen they are easily seen as rounded, clear patches. The whole rock has the character of a trachyte or phonolite with considerable olivine and augite in phenocrysts, and a fine granular groundmass. The biotite is mostly in small irregular grains or in patches molded between the feldspar grains; in part it grows about the magnetite or replaces the pyroxene or olivine.

A moderately large body of feldspar rock underlies the north slopes of Highwood Peak from an elevation of about 7400 feet to about 6700 feet. This rock is dark gray, rather fine granular, and has rounded, light-colored patches that are probably pseudoleucite. A specimen from an elevation of 7200 feet is about half-millimeter grained. It is made up chiefly of zoned feldspar (sanidine and hyalophane) and contains small, irregular, scattered grains of mafic minerals of which brown melanite exceeds biotite and pyroxene. The larger grains of pyroxene are zoned with light-colored cores of diopside ($X \wedge c = 48°$) and green borders that grade toward aegirite ($X \wedge c = 20°$, $\alpha = 1.722$, $\gamma = 1.748$). The smaller grains are of the green variety. The feldspar has cores of barium sanidine with specific gravity greater than 2.60 and α as high as 1.545. These cores grade to the border feldspar which has a specific gravity less than 2.55 and $\alpha = 1.520$. The average feldspar has about 12 per cent of celsian.

Some specimens lack olivine but have much biotite in the granular groundmass. In a specimen (FBH 545) from the east slope of the hill surrounded by the 5000-

foot contour northeast of Highwood gap the olivine is much resorbed and has reaction borders of pyroxene and iron ore and an outer zone of pale hornblende and pale-green biotite. The biotite phenocrysts are brown, and the groundmass biotite is green. The augite is in irregular crystals so filled with inclusions as to give it a sieve texture in places. In places it shows a little reaction to green hornblende. The groundmass is 0.2 mm. grained. The sanidine has some barium. An approximate mineral composition is

	Per cent	
Olivine	10	
Pyroxene	12	
Biotite	8	
Labradorite	(An_{54}) 20	Twinned β from 1.556 to 1.564, average 1.560
Sanidine	50	γ varies from 1.527 to 1.537, average $\beta = 1.530$

One of the specimens taken from a flow (F.B.H. 666) from the northeast slope of Highwood Peak in Deer Creek at an elevation of about 6700 feet is much like the leucite (or analcime) phonolites with larger phenocrysts in a fine groundmass. The leucite (or analcime) phenocrysts have been replaced by a rather coarse aggregate of orthoclase and cloudy analcime. The olivine has been much resorbed, and the smaller grains have been completely resorbed. The larger grains have a narrow layer, next the olivine, made up of grains of iron ore and indistinct material; beyond this is a broader zone fraying out into the groundmass and made up chiefly of a fine aggregate of dark-green biotite with some brown biotite and serpentine. The pyroxene phenocrysts have a very narrow border of green biotite in aggregates. There are several generations of biotite. The oldest are a few millimeter-sized phenocrysts that have been much resorbed. They have an irregular inner zone of pale biotite; beyond this is a narrow irregular zone of magnetite dust, and then a broad zone made up of an aggregate of very small biotite plates, mostly dark green but partly brown. There are biotites of intermediate size that show no resorption and are strongly zoned with pale-brown cores and dark-brown borders. There are some small dark-brown biotites in the groundmass and a green biotite replacing the olivine. Photomicrographs of specimens of this rock, in which the pseudoleucite is beginning to merge with the groundmass, are shown in Plate 5.

In only 2 out of 85 thin sections of the mafic phonolite volcanics examined was plagioclase found. These were both of about the same type of rock. One was from the second highest point of the Highwood Peak area.

In chemical composition the pseudoleucite rocks must be much like the leucite phonolites, although they probably have somewhat less lime, iron, and magnesia.

Femic-rich phonolites.—Three specimens have the usual phenocyrsts of pyroxene and olivine, and some small biotite plates in an abundant groundmass made up of random feldspar laths filled between with much analcime or natrolite. The groundmass is that common to many phonolites rich in zeolitized nepheline. These specimens came from: (1) north slope of Merrill Mountain, (2) north slope of Cottonwood Creek at an elevation of 5260 feet, and (3) Timber Creek, near the base of the phonolite.

Miscellaneous basaltic rocks.—A single specimen (L 29) of a dark-green rock made up of about 75 per cent of augite was collected in Packard Creek about 0.1 mile above the mouth. This rock has large pyroxene grains in a matrix of finer pyroxene with irregular patches of oligoclase and nepheline (now zeolites) inclosing pyroxene. There are a few streaks of intergrown feldspar and analcime. A little

pale-green phlogopite, magnetite, apatite, and perofskite (?) occur. Some of the large pyroxenes are broken.

Another specimen (F.B.H. 204), collected from near the top of Highwood Peak, shows in the hand specimen no phenocrysts but has irregular biotite and a somewhat streaked appearance. It is made up mostly of barium sanidine and sanidine, some zeolite, much biotite in coarse patches of bent plates, and pyroxene in aggregates of fine grains. The biotite and pyroxene are in streaks, and the whole rock has the appearance of autogranulation and streaking.

A specimen (F.B.H. 121), collected from the point of the ridge 2 miles N. 65° E. of Woodcock School, is fine-grained and has small rods of augite and flakes of pale biotite in a clear isotropic to indistinctly birefracting matrix; this matrix has an index of refraction just below that of balsam and is probably glass.

CHEMICAL ANALYSES

The foregoing discussion shows that the mafic analcime phonolites and rocks of about their chemical composition make up over two-thirds of the volcanic rocks, and mafic leucite phonolites (jumillite) and sanidine rocks most of the balance. An analysis of a typical fresh analcime phonolite and of an intrusive leucite rock similar to the leucite phonolites, but coarser in texture and richer in leucite, have been made by F. A. Gonyer. These analyses, the norm, modes in weight and volume per cent, and those of one of the leucite phonolites quoted from Pirsson are given in Table 2.

TABLE 2.—*Analyses, norms, and modes of extrusive mafic phonolites from the Highwood Mountains, Montana, and of similar rocks*

	Analyses						
	1	2	3	4	5	6	A
SiO_2	46.08	47.98	46.62	50.78	46.51	51.52	48.0
TiO_2	.61	.58	.76	1.28	.83	.75	.6
Al_2O_3	12.04	13.34	12.48	9.05	11.86	15.01	13.4
Fe_2O_3	4.58	4.09	4.78	2.96	7.59	3.75	4.2
FeO	4.02	4.24	4.44	3.64	4.39	4.37	4.2
MnO	.15	tr	.09	.09	.22	.07	.1
MgO	9.56	7.01	8.90	14.29	4.73	4.72	7.5
CaO	10.98	9.32	11.94	5.29	7.41	7.20	9.3
Na_2O	3.11	3.51	1.97	1.05	2.39	3.28	3.3
K_2O	2.90	5.00	4.42	7.39	8.71	5.46	4.6
H_2O-					1.10	.29	
H_2O+	4.56	2.10	2.83	2.53	2.45	1.96	
CO_2	none	1.24		.46		none	
P_2O_5	.94	1.03	.18	1.31	.80	.57	.8
SO_3		tr			tr		
S	tr		.05			.03	
BaO		.50	.60		.50	.56	.5
SrO		.14	.04		.16	.20	.2
CuO					tr		
Cl		.21			.04		
NiO					.04		
	99.53	100.29	100.10	100.12	99.73	99.74	
Cl=O		.07			.01		
		100.22			99.72		

TABLE 2.—*Analyses, norms, and modes of extrusive mafic phonolites from the Highwood Mountains, Montana, and of similar rocks*—Continued

NORMS

	1	2	3	4	5	6	A
or	17.24	29.47	16.12	43.92	13.90	32.35	
ab	8.91	5.76		4.72		17.29	
an	10.84	5.84	12.79	0.28		10.01	
ne	9.37	12.78	9.09		6.53	5.68	
lc			7.85		29.65		
di	29.85	26.83	36.82	14.17	25.42	19.09	
ac				3.23	7.39		
ol	8.93	5.68	5.58	22.56	1.88	4.68	
mt	6.73	6.03	6.96	2.78	7.42	5.57	
il	1.32	1.22	1.52	2.43	1.52	1.37	
ap	2.02	2.35		3.02	2.00	1.34	
Position	III.6″.2.3	III.6.2″.3(4)	III.7(6).2(3).(2)3	III.5.1.1(2)	III.8.1.2	III.″5.″2.3	

MODES

(Per cent)

	Vol.	Wt.	Wt.	Vol.	Wt.	Vol.	Wt.	Wt.	Vol.
Leucite			*	13	12	34	29	*	41
Analcime	37	30	33	9	8			37	
Hyalophane	11	10	11			10	9	6	
Sanidine									11
Base	8	8	8	45	37	17	17		
Augite	29	31	34	17	21	29	32	44	20
Olivine	11	13	14	9	12	6	7	9	17
Calcite				2	2				
Apatite				1	2				
Iron Ore	4½	8	8	4	7	2½	4½	4	3
Phlogopite									8
Katophosite									
Johannsen	2121			2121		2121			2121

Analcime	9
Hyalophane	8
Base	60
Augite	21
Olivine	3
Johannsen	2117

1. Mafic analcime phonolite (F.B.H. 169) from west end of ridge east of Geraldine-Geyser road and west of Round Butte. A fresh rock with phenocrysts of augite up to 4 mm. long, olivine up to 1 mm. long, clear analcime up to 1 mm. across in a groundmass made up mostly of zoned barium sanidine molding between the other constituents, partly replacing the analsime phenocrysts, and enclosing much pyroxene, analcime, and iron ore. The olivine has borders of iddingsite and the analcime is slightly clouded, but the rock is fresh. Analysis by F. A. Gonyer. Rosiwal by E. S. Larsen, 3d.

2. Mafic leucite phonolite (leucite basalt of Pirsson (1905, p. 168, 169)) from saddle between Highwood and Pinewood peaks. H. W. Foote, analyst. Rosiwal by L. V. Pirsson.

3. Mafic leucite phonolite (F.B.H.S. 247). Massive body southwest slope of North Peak about half way to top and southeast of the schoolhouse. A description of this rock is given on page 1745.

4. Jumillite. LaCella, Jumilla, Murcia, Spain. Described by Osann (1906, p. 290). Volume per cent by Tröger (1935, p. 21).

5. Leucitite, Bearpaw Peak, Bearpaw Mts., Mont. H. N. Stokes, analyst (Pirsson (1905), p. 168).

6. Mafic analcime phonolite (F.B.H.L. 114). Thin section 500 mm². Groundmass is very fine and is made up of sanidine, pyroxene, and much cloudy isotropic material. Described on page 1744.

A. Estimated average composition of mafic phonolite extrusive rocks of the Highwood Mountains.

* Estimated from heavy-solution separation.

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OUTCROPS OF DIKES

General view westward from Round Butte showing numerous dike exposures east of the Highwood Mountains.

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IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA

Part III. Dikes and Related Intrusives

BY B. F. BUIE

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ABSTRACT OF PART III

The dikes were classified under five field types, which in the order of their intrusion are: (1) amphibole phonolite, (2) pseudoleucite mafic phonolite, (3) augite mafic phonolite, (4) biotite phonolite, and (5) syenite porphyry. The rare amphibole phonolite dikes appear to be related to the quartz latite volcanics. The other four types form a gradational series related to the mafic phonolite volcanics. Types (2) and (3) constitute more than half the dikes of the area, and type (4) approximately one-fourth. Syenite porphyry and a few dikes of nepheline syenite, monzonite, and alnoite constitute the remainder.

The dikes vary in width from less than 2 feet to more than 20 feet. Few segments can be traced continuously for as much as a mile. Dikes are most numerous north and east of the mountains, where a radial trend out from the mountains is clearly recognizable. Fractures into which the dikes were intruded were produced by a centrally acting force and developed outward from the central part of the area.

An irregular intrusive body composed of alnoite and monticellite peridotite containing 32 per cent of monticellite was mapped 3 miles northeast of Geraldine.

A new term, headed dike, is proposed for intrusive bodies like the one found 8 miles southwest of Geraldine. This body is linear in plan and bulbous in cross section narrowing downward to a feeder dike. The top contact is conformable with the bedding of the Cretaceous sandstone. Fergusite and shonkinite are the principal rocks of the headed dike. Differentiation of the two types was gravitative after intrusion.

INTRODUCTION

In undertaking an investigation of the dikes and related intrusives of the Highwood Mountains area, it was thought that: (1) A more thorough mapping of the dikes than had been done by Weed and Pirsson might give information pertaining to the structural factors involved in their intrusion; (2) the determination of the sequence of intrusion of dikes of different petrographic types would indicate a progressive change in the chemical and mineralogical constitution of the magma in the magma reservoir; (3) possibly a correlation could be established between certain types of dike rock and individual stocks thus providing a means of determining the sequence of eruption of the stocks; (4) a petrographical study of a large number of individual dikes, with especial attention to the differences between the central and the chilled border phases, might reveal petrographical and mineralogical features which had been overlooked by Pirsson in his study of the igneous rocks of this unusual province.

A base map was compiled from the county surveyors' maps of Chouteau, Cascade, and Judith Basin counties. This map, having a scale of 1 inch equals 2 miles, was satisfactory for plotting the dikes in the southern and western part of the area. In the northern and eastern part, where the dikes are much more numerous, the Chouteau County land classification plats on a scale of 1 inch equals ¼ mile were used for the field mapping, and plotting of the dikes was later transferred to the compiled base map. In the territory around the mountains, pace and compass traverses at approximately half-mile intervals were made where the dikes are most numerous, and elsewhere motor traverses supplemented by pace and compass traverses were spaced closely enough to locate most of the dikes. In the areas of volcanic rocks many dikes remain unmapped, but from these enough samples were collected and studied to show the types represented. The dikes mapped are shown on the geologic map in the related paper by Larsen (1941). Detailed plane-table maps of several unusual bodies were prepared.

During the field investigation a thorough study of the sills was not undertaken, but occasionally observations were made upon the sills and specimens collected from them at localities where relationship with or similarity to the dikes was indicated; the results of some of this incidental work are included in this report.

In addition to the usual petrographical studies, several new chemical analyses of rocks and minerals have been obtained.

PHYSICAL FEATURES OF THE DIKES

NATURE OF EXPOSURES

In the volcanics and metamorphosed sediments of the mountains the erosion of the dikes proceeds at about the same rate as that of the country rock; this, in connection with the close similarity in appearance of the volcanic and dike rocks and the greater amount of vegetation in the mountains, makes the tracing of individual dikes for more than very short distances extremely difficult.

The sandstone and shale around the mountains have not been metamorphosed except in the immediate vicinity of each dike, and in this part of the area the dikes are generally more resistant than the unmetamorphosed sediments. Consequently, the dikes here hold positions along the crests of small ridges or form rock walls up to 80 feet in height. Many of the less resistant dikes are weathered out from between two narrow walls of metamorphosed sandstone, which rise a few feet above the general surface (Pl. 1).

Around the mountains considerable areas of benchlands and terrace deposits obscure the bedrock. Therefore, in many areas the lack of dikes on the map is due to lack of exposures. In general, the exposures are better northeast, east, and southeast of the mountains, where the drainage of Arrow Creek and other direct tributaries of the Missouri River have partially cleared away the terrace deposits and cut into the weak sandstone and shale bringing the dikes out in relief. The combination of few dikes and poor exposures in the western part of the area made it unwise to spend the time necessary for traversing closely enough there to be certain of locating every possible dike exposure. Accordingly, a few dikes which are exposed in that part of the area may have been missed, but if they had been plotted on the map its major features would not have been materially changed.

Continuous dike exposures more than a mile long are unusual. Much more commonly a dike segment pinches out, is interrupted by a fault, or becomes covered within less than a mile. Certainly many segments continue for greater distances than represented on the map, but in the course of the field mapping each segment was plotted only for the distance it was known or could safely be inferred to be present. This gives a dike pattern somewhat different from that shown by Pirsson (1905, Pl. III), but it is a more exact representation of the actual field observation of the dikes.

Many dikes of the biotite-rich nonresistant rock are deeply weathered and outcrop only as strips of gravelly soil, although even this weak material may be resistant enough to form a low ridge. Some of these dikes are made more easily recognizable by the growth of a distinctive type of vegetation or by the paucity of vegetation along their courses.

SIZE

The dikes vary in width from less than 2 feet to more than 20 feet, but most are between 4 and 10 feet. One conspicuous dike south of Round Butte is 25 feet wide, but with the exception of several dikes of unusual form and structure to be described individually there are few whose width exceeds 20 feet. Normal dikes having a width of 20 feet or more were found only in the eastern part of the area, and these were all composed of augite mafic phonolite or pseudoleucite mafic phonolite.

FORM

The dikes and related intrusives of the Highwood Mountains area show great variation in form. Some are of such unusual form as to warrant separate description, and a few are so irregular that no term except Chonolith applies (Daly, 1933, p. 105). One is so unlike any body which has been well described previously, yet has such definite form, that a new name—the headed dike—has been proposed for it. Even the bodies which are dikes in the strict sense of the word show considerable variety of form, and this is particularly true of the dikes of biotite phonolite. The two walls of many individual dikes locally are not parallel, and local variations in width result. Where traced up a vertical cliff one contact may be vertical, while the other flattens locally to parallel the bedding for several feet before returning to a vertical trend. Some of the dikes split into two portions, and in horizontal or vertical section one of the portions may pinch out in a distance of a few feet. Abrupt changes in dip are not rare, and for short distances some dikes parallel the bedding planes of the sedimentary strata and become sill-like. However, these local sills are not to be confused with the numerous true sills of great areal extent which are present in the area.

Occasionally a dike is seen which instead of following a consistent strike makes a series of sharp turns, thus forming a series of connected segments of which only the alternate ones have the same strike. The zig-zag course suggests that such dikes had their positions controlled by intersecting sets of joints.

About 7 miles northwest of Geraldine, and half a mile west of the road toward Fort Benton, a conspicuous ridge of igneous rock stands above the

generally eroded surface. The exposed width of the igneous body ranges from less than 50 to nearly 100 feet. The contact with the country rock is obscured on one side, but on the other a clearly discordant contact can be seen. For 4 feet from the contact the sandstone beds are crumpled, and at one place a sill 2 inches thick has been injected for several feet. The top of the ridge has a gentle, uniform, longitudinal slope and a somewhat rounded cross-sectional form. On one side the sandstone beds extend partially over the top, and locally a distinctive chilled phase of the intrusive rock extends entirely across the top. Accordingly, it seems reasonable to suppose that this is a dike which terminated upward at the present position of the erosion surface.

STRUCTURAL FEATURES

ROCK TYPES AND SEQUENCE OF INTRUSION

In the field the dikes were classified under five types and several subtypes. The five types in the order of intrusion are: (1) Amphibole phonolite, (2) pseudoleucite mafic phonolite, (3) augite mafic phonolite, (4) biotite phonolite, and (5) syenite porphyry.

The amphibole phonolite dikes are rare in the Highwood Mountains area, and their relationship with other dike types was not directly observed. However, they were found intrusive into only the older volcanic series, or the sedimentary strata, and never into the younger volcanic rocks.

The dikes of pseudoleucite mafic phonolite and those of augite mafic phonolite merge, and the microscopic studies have shown that there is no clearly defined distinction. In the field the dikes are mutually intrusive. The situation must have been one of partial rather than complete contemporaneity, however, for in most places the pseudoleucite mafic phonolite is cut by augite mafic phonolite. Further, within the augite mafic phonolite type there is a clearly exhibited tendency for the olivine-rich dikes to be cut by olivine-poor dikes.

The dikes of viotite phonolites show considerable variation, and it is possible that one subtype, rich in olivine, should be given a separate place in the sequence. The typical biotite phonolite dikes are younger than the augite and pseudoleucite mafic phonolite dikes. Numerous examples of demonstrable age relationships were observed, and in every one the biotite phonolite dike was the younger.

The syenite porphyry dikes are restricted in distribution and in number, but wherever one was observed at an intersection with a dike of another type the syenite porphyry was the younger.

RADIAL DISTRIBUTION OF DIKES

As may be observed on Plate 1 (Larsen, 1941), the most striking feature is the radial distribution of the dikes about the mountains as a whole. This is especially noticeable on the north and east sides of the mountains where the dikes are most abundant. A radial arrangement about the individual stocks, as suggested by Pirsson (1905, p. 32), was found to be pronounced only in the case of Shonkin stock. Only rarely was a dike observed having a tangential position. No structures comparable to ring dikes were observed. These factors undoubtedly have a bearing upon the structural conditions under which the dikes were intruded.

ZONAL DISTRIBUTION AROUND THE MOUNTAINS

Except in the case of the syenitic dikes, no marked tendency toward zonal distribution of the different types of rock present in the dikes was noticed. Although a considerable number of syenitic dikes occur within the mountains, none were found in the surrounding area of relatively undisturbed sedimentary strata. The augite and pseudoleucite mafic phonolite dikes are ubiquitous, but there appears to be a tendency to an increase in their biotite content toward the outer limits of the area.

NONUNIFORM AREAL DISTRIBUTION

As can be seen from the geologic map (Larsen, 1941, Pl. 1) dikes are much more numerous on the north, northeast, and east sides of the mountains. Although bedrock is not so well exposed in the western part of the area there are sufficient exposures along streams to justify the conclusion that dikes are comparatively rare there. This nonuniformity of dike intrusion is connected with the general structural condition of the Highwood Mountains and the surrounding territory. The nine laccoliths described by Hurlbut and Griggs in Part I of this paper (1939) are all on the east side of the mountains, and Reeves (1928, p. 168) found that thrust faulting was much more prevalent northeast of a northwest-southeast line through the center of the mountains. In addition to this general feature of distribution there is locally a marked tendency for a number of dikes of the same petrologic type to be closely spaced and parallel, thus producing local "dike swarms."

RELATIONSHIP OF DIKES TO OTHER IGNEOUS BODIES

Although the dikes are radial around the mountains as a whole, and to a slight degree around the individual stocks, they are not apophyses of the stocks. It has not been possible on a structural basis to correlate any one type of dike with any specific stock. With the exception of the amphibole phonolite, representatives of all the five field types have been

observed intrusive into the stocks. No example of a dike cut off by a stock was found. Generally, dikes are particularly numerous in the vicinity of a stock. This situation is the result of a large amount of fracturing which occurred after rather than during intrusion of the stocks.

Dikes of all types are intrusive into the older (quartz latite) volcanic series, and all types except amphibole phonolite are intrusive into the younger (mafic phonolite) series. There is no distinction between the number of dikes in areas of volcanic rocks and in areas of sedimentary rocks. There is no field evidence to indicate that the dikes served as channelways for the extrusion of the volcanic materials.

There are comparatively few dikes which cut the laccoliths, a fact which will be remarked upon further in the discussion of mechanics of intrusion. Three dikes of biotite phonolite are intrusive into the Shonkin Sag laccolith, and at least one dike of mafic phonolite cuts the Square Butte laccolith. The amphibole phonolite dikes are believed to be older than the laccoliths, and the syenite porphyry dikes are restricted to parts of the area where there are no laccoliths.

The sills are genetically closely related to the laccoliths, and the same structural relationship exists between the dikes and the sills as between the dikes and the laccoliths. Particular search was made for dikes which served as feeders of the sills, but no dike was found which clearly served as a feeder for a sill of any appreciable extent.

The Haystack Butte chonolith forms an isolated outcrop, and its relation to the dikes cannot be determined.

Two dike segments strike into the headed dike, but they do not cross it, and neither can be found continuing in its line of strike on the opposite side. They probably were faulted before the headed dike was intruded. These dikes are micaceous augite mafic phonolite and belong to the same general type as the headed dike. No structural relationships between the headed dike and dikes of other petrographical types have been observed.

COMPOSITE AND MULTIPLE DIKES

The terms "composite" and "multiple" have been applied to igneous intrusions with a variety of meanings by different authors. The term "composite" seems to have been used first in describing the Tertiary igneous rocks of the British Isles, but subsequent workers there have not been consistent in their use of it (Harker and Clough, 1904; Bailey and others, 1924, p. 32). Daly (1933, p. 91-92) defines multiple and composite dikes as follows:

"Multiple dikes are intrusions of dike form, due to successive injections of one kind of magma into the same, intermittently widened fissure.

"Composite dikes were formed by successive injections of chemically differing melts into the same fissure which widens to receive them."

Applying Daly's definitions, there are a number of composite dikes and a few multiple dikes in the Highwood area. A typical composite dike crops out on the upper slopes of the benchland east of North Peak

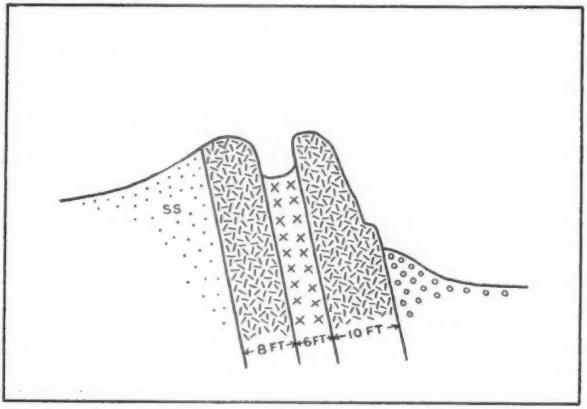


FIGURE 1.—*Vertical cross section of a composite dike*

and about half a mile from the base of the mountain. The marginal members are augitic mafic phonolite, 8 feet and 10 feet wide, respectively; the central member is light-colored biotite phonolite, 6 feet wide. The central rock is weaker and has weathered out to form a trough between the more resistant marginal rock. (*See* Figure 1.)

One of the best examples of a composite dike was found in sec. 2, T. 21 N., R. 10 E., east of Lepley's Creek and on the east edge of the abandoned channel of the Missouri River, known as the "Shonkin Sag". A porphyritic rock with phenocrysts of biotite and green pyroxene constitutes the central 3 feet; the two flanking members, each about 4 feet wide, are composed of darker, though somewhat similar, rock containing numerous inclusions of augite phonolite. The central member maintains a uniform width, as does the composite as a whole, but the width of the individual flanking members varies because the central member locally approaches either one or the other of the sedimentary contacts. The central member has a 2-inch chilled phase on each side at its contact with the darker rock. The composite relationship persists for 0.4 mile, beyond which the central member cannot be traced in the outcrop.

About 14 miles south-southwest from Geraldine and half a mile south of Cottonwood Creek the road between Geraldine and Geyser cuts through a large wall dike. Immediately east of the road at this locality the following relationship can be observed: A dike of augite mafic phonolite 20 feet wide strikes S. 45 E.; a 4-foot dike of biotite phonolite

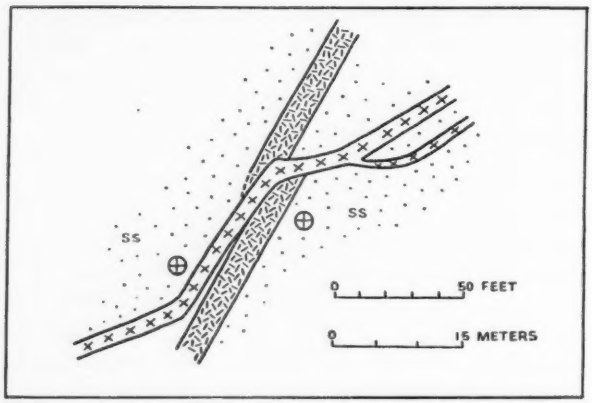


FIGURE 2.—*Dike of mafic augite phonolite intersected and displaced by a dike of biotite phonolite*

striking S. 30 E. abuts against the other, then turns and follows along its northeast contact for 150 feet before turning again to cut abruptly across it. Rock debris from the larger dike obscures the biotite phonolite dike southeast of the intersection, but float of similar biotite phonolite there indicates that this dike resumes its normal strike of S. 30 E., after having been locally diverted to form a composite dike with the augite mafic phonolite for a short distance.

A quarter of a mile north of the road along the valley of Cowboy Creek 2 miles west of the town of Square Butte, a 6-foot-wide dike of biotite phonolite locally parallels a dike of augite mafic phonolite, as shown in Figure 2. A composite relationship is simulated, but a narrow layer of sandstone separates these two dikes, and they cannot be considered as composite even locally.

Three dikes of distinctly different rock in parallel juxtaposition were observed at a few places, as on the ridge west of the upper part of Alder Creek. In most instances, however, only two types of rock are involved, and these are most commonly biotite phonolite and augite mafic phonolite. In the Highwood Mountains area a dozen or more such composite

dikes were observed, and it is probable that numerous others are present, especially in the mountainous terrain.

Multiple dikes, as defined by Daly, are not common in the Highwood Mountains area. Such dikes would be difficult to recognize except those in which the earlier injections had cooled sufficiently to cause chilling of the later injections. If differentiation proceeded rapidly in the magma reservoir during the interval between these successive injections different types of rock would be introduced, and the dike would then be composite rather than multiple. The dike of biotite phonolite represented in Figure 2, in addition to its composite relationship with the augite mafic phonolite, exhibits evidence of multiple injection. Where it cuts across the augitic dike a 4-inch-wide chilled phase is developed, and within the biotite phonolite eight chilled zones each 2 to 2.5 inches wide indicate at least four injections of this magma.

A third and distinctly different structural type of dike found rarely in the Highwood Mountains area may fulfill the requirements of a composite dike as defined by Bailey and others (1924, p. 32). Their definition imposes three conditions, as follows:

(1) Composite intrusions are composed of parts of recognizably different composition.
(2) As a complex they chill exteriorly against country rock.
(3) The component parts do not chill against one another—if they do the intrusion is multiple not composite.

As seen in the field, many dikes in the Highwood Mountains area simulate these conditions; chilling of the marginal portion of the dike has prevented the disintegration of pseudoleucite and has hindered the development of visible biotite but the central and marginal members do not differ in composition. A few dikes were observed in which the component parts do consist of rock of at least slightly different composition, yet show no chilling of one component against another. Two of these dikes will be described.

The first crops out a quarter of a mile east of the road between Geraldine and Geyser, and about 0.2 mile north of Cottonwood Creek. A dike 15 feet wide has on each side a more resistant marginal phase of augite mafic phonolite which varies from 8 inches to 2 feet in width (FBD 212). The central 10 to 12 feet of rock is more micaceous and contains more small masses of zeolites (FBD 213); it also contains inclusions (FBD 213) of resistant rock like that of the margins. No sharp line of demarcation separates the two types of rock. Apparently, the central portion was intruded before the marginal portion had entirely crystallized.

Another such dike is locally exposed at the southwest end of Sand Lake, in sec. 25, T. 22 N., R. 9 E. It strikes N. 25 E. and consists of three units. The westerly unit, 8 feet wide, and the easterly unit, about 6 feet wide, are augite mafic phonolite (FBD 468) with occasional large crystals of olivine. The central unit, 8 feet wide, is micaceous augite mafic phonolite with much more olivine in large euhedral crystals up to 1.7 cm. in length and 1 cm. in thickness. There is no sharp contact between the central and marginal members; the transition between the two types of rock occurs within a few inches. The central member represents magma richer in olivine; it came in before the marginal members were entirely cooled and was either a separate injection or a late phase of a single injection in which the composition of the magma changed slightly during the course of the injection.

NODULAR WEATHERING

A dike of biotite phonolite, east of the point where the road from Geraldine toward Geyser reaches the floor of Shonkin Sag, shows an unusual weathering to hard round balls imbedded in a softer matrix. The outcrops look like those of a conglomerate with very round pebbles. A photograph of the dike is shown in Figure 1 of Plate 2, and one of the nodules on a larger scale in Figure 2. The balls, which are a few inches across, weather out, and some parts of the dike look like piles of small cannonballs. Thin sections of the balls and the matrix show the rock to be mafic phonolite with abundant biotite phenocrysts. The groundmass of the matrix is rather coarse and is made up chiefly of orthoclase and altered nepheline. The balls are similar to the matrix but have a somewhat finer goundmass. They probably are auto-inclusions formed by the incorporation within the magma of fragments of partially chilled rock from near the contacts.

ORIENTATION OF PHENOCRYSTS

Many of the dikes intrusive into the sedimentary beds at the east side of the Highwood Mountains show a marked linear orientation of the phenocrysts. This is especially noticeable in the dikes carrying relatively long prisms of pyroxene or amphibole. A distinct orientation can be observed in 10 per cent or more of these dikes. It is well shown in the headed dike. The prisms are oriented with their long axes in a plane parallel to the wall of the dike and predominantly in a horizontal position. Commonly, the degree of orientation is greater in the margins of the dike. Two possible explanations can be offered: (1) movement of the dike magma horizontally, orienting the long axes parallel to the direction of flow; (2) continued upward movement of the magma in the central

FIGURE 1. "CANNONBALL" DIKE

FIGURE 2. DETAILS OF THE "CANNONBALLS"

FIGURE 3. SMOOTH, WEATHERED SURFACE OF FERGUSITE
Showing conspicuous pseudoleucite.

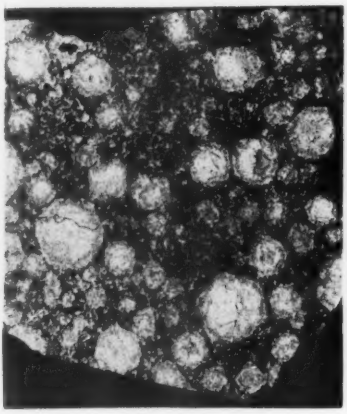


FIGURE 4. PLANE GROUND SURFACE
Slightly darker border of pseudoleucite is sanidine. Natural size.

"CANNONBALL" DIKE AND HAND SPECIMENS OF FERGUSITE

FIGURE 1. CHONOLITH C IN THE FOREGROUND, E IN THE LEFT BACKGROUND

FIGURE 2. ROUNDED INCLUSIONS IN BIOTITE PHONOLITE

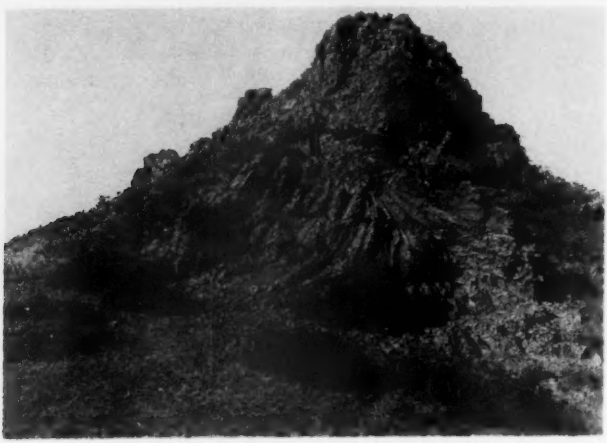


FIGURE 3. CHONOLITH B, SHOWS FLARING OF JOINTS

VIEWS OF INTRUSIVE BODIES NEAR COAL-MINE COULEE

part of the dike after the magma nearer the margins had become highly viscous, thus creating a shearing action which oriented the long axes in the plane of shearing and at right angles to the direction of movement.

In the dikes which contain well-developed tablets of feldspar these tablets are commonly oriented with the large face parallel to the walls of the dike. In many of the biotite phonolite dikes tabular phenocrysts of biotite show a similar orientation.

MECHANICS OF INTRUSION

The radical pattern of the dikes around the mountain area shows clearly that the dikes were not individually responsible for producing the fractures into which they were injected. A more general force was responsible, and the dikes worked their way along the fractures produced.

Evidence of the amount of intrusive force exerted by the individual dikes is meager. Rarely the beds of sedimentary rock are crumpled for a few inches from the contact, but whether this deformation was produced coincident with the intrusion of the dike or later cannot be determined. The magma of the headed dike had sufficient force to lift the roof of sandstone over it, but it is believed to have been intruded at shallow depth.

East and southeast of the mountains, in several instances where two dikes intersect, the younger dike follows along the contact of the older dike for a few tens of feet before breaking across and resuming its general strike. In all of these, the younger dike lies on that side of the older dike which is toward the center of the mountains. The fractures for these dikes were formed by splitting of the country rock outward from the center of the area, rather than upward. Such a relationship can be observed only under favorable conditions of exposure, and it is not possible to state how well the few examples observed represent the general conditions.

The area occupied by the Square Butte, Round Butte, and Shonkin Sag laccoliths have distinctly fewer dikes than the adjacent territory. Immediately west of Round Butte dikes are abundant, and several are present near the bottom of the slope at the northwest corner. Dikes are also present both north and south of Round Butte. Along the west side of Round Butte the upper rim has excellent rock exposures, but a careful search revealed no dikes there. Dikes, if present at all, are certainly much rarer in the main mass of the Round Butte laccolith than in the sedimentary rocks to the north, west, and south. Hurlbut has made a thorough study of Square Butte laccolith and he recalls only one dike intrusive into that body. The writer's observations agree with Hurlbut's

opinion that dikes cutting Square Butte laccolith are rare. Between Round Butte and Square Butte the terrain is favorable for bedrock exposures, and the outcrop of a horizontal sill can be followed for a mile, but there is only one dike exposed. This is in sharp contrast to the great number of dikes immediately west of Round Butte. On the east side of Square Butte rock debris partially obscures the bedrock exposures, but sufficient gulches are cut through to show that dikes cannot be nearly so prevalent here as on the west side of Round Butte. These facts point to the conclusion that, during the various episodes of fracturing which preceded or accompanied each episode of dike intrusion, the stronger rock of the laccoliths held rigidly together and resisted fracturing. Further, the much larger number of dikes to the west of Round Butte than to the east of either Round Butte or Square Butte indicates that the development of fractures proceeded from west to east—that is, outward from the center of igneous activity—and were impeded by the rigid block which contained the Round Butte and Square Butte laccoliths.

DESCRIPTIONS OF THE DIKE ROCKS

AMPHIBOLE PHONOLITE

Dike rocks containing amphibole are extremely rare in the Highwood Mountains area. The type of rock referred to as amphibole phonolite is porphyritic, with slender prisms of glistening dark-green or black amphibole up to over 10 mm. in length embedded in a dense, nearly white groundmass. Petrographically, it appears to be related to the earlier, quartz latite, volcanic series, and this is in accord with the structural relationships already discussed. Isolated faulted segments of such a dike are present in the quartz latite volcanics 0.5 to 1 mile west of the road between Geraldine and Geyser and about 1 mile north of Cottonwood Creek. A dike of very similar rock crops out at the north edge of the valley of Cottonwood Creek 1.3 miles west of the Geraldine-Geyser road.

The first of these rocks (FBD 203) contains about 5 per cent of phenocrysts of green hornblende in a much finer groundmass. The hornblende is strongly zoned and much resorbed, and clustered around it are closely packed slender 0.05 mm. prisms of pyroxene (?) which have an extinction angle near 45 degrees. Some weakly birefracting zeolite masses occupy irregular areas in the section, and some fresh leucite may be present. There are a few phenocrysts of apatite 0.5 mm. long. The groundmass is composed of about 70 per cent of 0.2 mm. tablets of sanidine, and the balance of fine pyroxene (?) prisms and ½ per cent of small grains of magnetite.

The rock of the other dike mentioned (FBD 193, 194) is similar except that much of the feldspar is coarser, and there is about 5 per cent of strongly pleochroic biotite present. The rock has a few phenocrysts of 3 mm. tablets of biotite and an occasional large tablet of barium sanidine, one of which measured 20 by 13 by 7 mm. The amphibole phonolite is the rock described by Pirsson (1905, p. 132-136) as gauteite. An analysis of this rock from a dike in the upper valley of Aspen (Cottonwood) Creek is quoted from Pirsson in column 6 of Table 1.

TABLE 1.—*Chemical analyses, norms, and modes of dike rocks of the Highwood Mountains*

	ANALYSES								
	1	2	3	4	5	6	7	8	A
SiO_2	46.04	46.92	47.82	49.26	51.94	55.23	57.18	58.04	47.8
TiO_2	.64	.65	.67	1.11	.39	.42	.30	.30	.7
Al_2O_3	12.23	14.04	13.56	13.64	15.78	18.31	18.54	17.25	13.5
Fe_2O_3	3.86	3.76	4.73	1.72	4.07	4.90	3.65	2.49	3.5
FeO	4.60	5.07	4.54	7.76	3.17	2.06	1.15	1.24	5.5
MnO	trace	.12	trace	.12	trace	trace	trace	trace	.1
MgO	10.38	8.06	7.49	8.31	3.48	1.85	.69	1.79	8.3
CaO	8.97	10.02	8.91	8.42	6.04	3.62	2.31	3.50	9.1
Na_2O	2.42	2.87	4.37	1.90	3.44	4.02	4.48	3.37	2.7
K_2O	5.77	4.33	3.23	5.02	7.69	6.43	8.58	10.06	4.4
H_2O+	2.87	2.36	3.37	*1.21	2.17	1.84	2.10	1.95	
H_2O-		.36		.32					
CO_2		.12							
P_2O_5	1.14	.79	1.10	.75	.59	.58	.05	.22	.9
S		.04		.02		.23			
SO_3	trace		trace		.29	.46	.06	trace	
BaO	.48	.26	.16		.42	trace	.49	n.d.	.3
SrO	.25		.21		.28	.32	trace	n.d.	.2
Cl	.11		.04		.08		.77	trace	.1
Li_2O								trace	
	99.76	99.77	100.20	99.56	99.83	100.27	100.35	100.21	
Cl=O	.03				.02	.08	.17		
	99.73				99.81	100.19	100.18		
	NORMS								
or	21.68	25.58	18.50	29.47	45.59	37.81	50.60	59.40	
ab	.....	8.38	16.77	10.48	8.91	34.06	26.20	14.69	
an	5.28	12.51	7.78	10.48	6.12	12.79	8.34	3.34	
lc	11.03								
ne	11.08	8.52	11.08	3.12	9.66		3.12	6.25	
hl					.57		1.29	.59	
di	26.72	21.68	23.49	17.49	16.09	1.08	2.58	9.29	
ol	12.72	10.85	7.77	14.74	1.99	2.80	.42	.14	
hy						0.10			
mt	5.57	5.57	6.73	2.55	6.03	5.57	2.78	3.02	
il	1.22	1.22	1.22	1.98	.76	.76	.61	.61	
hm						1.12		.32	
ap	.69	2.02	2.69	2.35	1.34	1.34		.67	
Position	III.7. "2.(2)3. "III	6(5). "4.3	III.6. 2".4	(II)III. 5.2(3). 2(3)	II.(5)6. (1)2. 3(4)	(1)II. 5.2.3	I".5. I2.3	(I)II.5". 1".2"	

TABLE 1.—*Chemical analyses, norms, and modes of dike rocks of the Highwood Mountains (continued)*

	MODES								
	1	2	3	4	5	6	7	8	A
Sanidine	45			50	71	42±	50	65 to 70	
Oligoclase				7		42±	13		
Leucite Pseudoleucite			15?						
Analcime			30					10 to 15	
Nepheline (altered)						?			
Sodalite							10		
Diopside	27	25	35	25	12		10	17	
Olivine	7	5	8	10					
Hornblende						10			
Biotite	16			5	10				
Iron Ore	4		8	3	5	5	2	3	
Apatite	1		2½		2½	1½			
Kaolinite							7		
Groundmass		70							
Johannsen	3218(?)	2117	3121	2214	2218	2210	2218	2217	

1. Mafic phonolite with biotite (minette). Dike near Arrow Peak. H. W. Foote, analyst. Mode estimated by Pirsson.

2. Augite mafic phonolite (FBD 223) from dike wall at Geraldine-Geyser road; 0.5 mile south of Cottonwood Creek. F. A. Gonyer, analyst. Thin section 770 mm². Phenocrysts of augite 4 mm. long and olivine 1 mm. across, in a fine groundmass of pseudoleucite, with some biotite, pyroxene, and iron ore.

3. Mafic phonolite (analcite basalt of Pirsson). Dike on east side of Highwood gap. H. W. Foote, analyst. Mode estimated from the analyses by Pirsson. Probably contains feldspar and no leucite.

4. Augite mafic phonolite (FBD 351). Irregular intrusive in sec. 11, T.20N., R.11E. Thin section 520 mm². Maximum grain size 2 by ½ mm. Very fresh rock. F. A. Gonyer, analyst.

5. Nepheline syenite porphyry (syenite porphyry of Pirsson). Dike near Shonkin stock. H. M. Bradley, analyst. Rosiwal by Pirsson.

6. Monzonite porphyry (gauteite), Aspen (Cottonwood) Creek. H. W. Foote, analyst.

7. Sodalite syenite porphyry (tinguaite porphyry of Pirsson). Dike on ridge between Middle and South Peaks. E. B. Hurlburt, analyst. Mode calculated by Pirsson.

8. Syenite porphyry (tinguaite porphyry of Pirsson). Dike near head of Highwood Creek. E. B. Hurlburt, analyst. Mode estimated by Pirsson.

A. Estimated average composition of dikes of mafic phonolites.

AUGITE AND PSEUDOLEUCITE MAFIC PHONOLITE

General description.—In the field study of the dikes a distinction was made between those dikes which carry visible leucite or pseudoleucite in addition to augite and those in which phenocrysts of only augite were visible. Subsequent study in the laboratory has shown that these two types grade imperceptibly into each other and that whether pseudoleucite or granular sanidine is present depends at least in part upon rate of cooling. Accordingly, these two field types will be described together.

The rocks included in this group are made up chiefly of sanidine, altered nepheline (?), and mafic minerals and, therefore, fall into the broad group of phonolites. Mineralogically, they differ from ordinary phonolites in being for the most part rich in mafic minerals and in having considerable

olivine and some remnants of primary leucite and analcime. Texturally, they differ from ordinary phonolites in having commonly a large part of the sanidine and altered nepheline in the form of pseudoleucite[1]. The rocks might be considered as jumillites and analcime jumillites in which the leucite and analcime have been largely altered to pseudoleucite. Pirsson referred to these rocks as monchiquite and leucite monchiquite, but the presence of a considerable percentage of orthoclase in most of the specimens, either in pseudoleucite or as independent tablets, renders those terms unsuitable. There is sufficient variety so that several new names might be proposed if it were not deemed unwise to further complicate petrographical nomenclature.

Rocks of this group constitute more than half of all the dikes of the area. These rocks are very much like the extrusive pseudoleucite mafic phonolites except that they generally lack vesicules, carry less zeolites, and are generally less altered. They cover about the same range in chemical and mineral composition and in textures as the lavas, though the dike and sill rocks are on the average more coarsely crystalline. Dikes of this type do not commonly contain inclusions. The rock of an individual dike is uniform along the strike although marked textural differences may be observed between the chilled margins and the central portions, and in a few the margins and centers may have been formed from slightly different magma. (*See* Composite and Multiple Dikes.) Amygdules of zeolite up to 10 millimeters in diameter are present in a few dikes.

The majority of the rocks of this group are medium to dark gray to nearly black, porphyritic, with a dense groundmass and phenocrysts of augite usually between 2 mm. and 8 mm. in length. About half carry pseudoleucite as white trapezohedrons or spheroidal units which range from less than 1 mm. up to 8 mm. in diameter. Less frequently fresh leucite can be recognized by its greenish-white color. The units of pseudoleucite are much less sharply bounded in coarser rock than in the dense chilled phase. A small amount of olivine, somewhat altered, is generally present as 1 mm. to 3 mm. crystals.

The proportion of phenocrysts varies greatly from the average of about 40 per cent (by volume). A few specimens show only a few scattered inconspicuous prisms of augite in a dense groundmass, but the total phenocrysts commonly constitute between 20 and 50 per cent of the rock. Phenocrysts of pseudoleucite may be absent or may constitute as much as 30 per cent of the rock. A few of the larger dikes contain conspicuous euhedral crystals of olivine up to 2.5 mm. in length, in addition to the usual augite phenocrysts. Biotite usually is visible in the groundmass of the coarser-grained varieties, and large tabular phenocrysts are present in some specimens. As the proportion of biotite increases, this group of rocks grades into the biotite phonolites.

[1] Much of the material referred to as pseudoleucite may be pseudoanalcime, but as it is usually impossible to distinguish between the two the term pseudoleucite will be used for both.

Microscopic petrography.—The large wall dike which crosses the County road between Geraldine and Geyser, 14 miles south of Geraldine and half a mile south of Cottonwood Creek, is relatively fresh and is taken as representative of this group. An analysis of FBD 223 is given in Table 1, column 2. In thin section the rock (FBD 223, 224) shows very slight alteration of the feldspar but considerable zeolitization of the interstitial nepheline (?), and a little alteration of olivine. Phenocrysts make up 30 per cent of the rock, 25 per cent being augite and 5 per cent olivine.[2] These are embedded in a groundmass with about 50 per cent of pseudoleucite and additional sanidine, 15 per cent of augite, 3 per cent of biotite, and 2 per cent of opaque mineral.

The pyroxene phenocrysts are 4 mm. long, sharply outlined, and unaltered. They are zoned, colorless in the centers and pale green and faintly pleochroic toward the borders, but with some recurrent zones. There are numerous inclusions, chiefly of groundmass material but also some of colorless minute prisms and formless grains zonally arranged.

The olivine phenocrysts range from less than 0.5 to nearly 1 mm. They show fairly well developed crystal form and have been little absorbed, if at all. A small amount of alteration to yellowish-green serpentine (?) has occurred along cracks and margins. In a thin section from the margin of this dike the olivine is completely altered.

Biotite forms strongly pleochroic tablets, 0.05 to 0.3 mm. long, in the groundmass. No phenocrysts of biotite are seen in the central part of the dike, but the section from the margin shows several rounded and much resorbed tablets now about 0.5 mm. in diameter but obviously the remnants of somewhat larger tablets. This biotite is pale and faintly pleochroic except a very narrow margin which is darker and has stronger pleochroism. In this section are local aggregates of thin and narrow laths of intensely pleochroic biotite which simulates aegerite in appearance.

There are a few remnants of largely resorbed tablets of barium sanidine.

The pseudoleucite is not in sharply bounded units, even in the chilled phase, and the sanidine in it cannot be distinguished from similar low-index sanidine which crystallized independently. Much of the sanidine of the pseudoleucite is in fine radial or plumose aggregates with altered nepheline (?). In the central part of the dike the groundmass and the texture of the pseudoleucite are coarser than in the marginal rock, and the pseudoleucite merges indistiguishably with the groundmass. Its presence can be recognized in thin section by the peculiar intergrowths of feldspar and nepheline (?) and by the circular areas devoid of dark minerals.

The pyroxene in the groundmass is like that of the margins of the phenocrysts; prisms are from under 0.1 mm. to about 0.5 mm. in length but are commonly 0.2 mm. The pyroxene prisms from the chilled margins of the dike commonly are only a little shorter but considerably thinner than those from the central portions.

The dikes of augite and pseudoleucite mafic phonolite are very similar to the mafic phonolite volcanics. Approximately the same petrographical varieties exist in the two groups, and the descriptions of subtypes in Part II of this paper (Larsen, 1941) apply almost as well to the dikes as to the volcanics. Clear analcime phenocrysts more or less altered to pseudoleucite were found in about 10 per cent of the dike specimens studied in this group of dikes, and clear leucite in about 2 per cent. Either andesine or labradorite was found in about 2 per cent.

Barium sanidine, having an index of refraction near balsam, is present in a few sections. It is in tablets 0.5 to 1 mm. long, showing Carlsbad twins. It has sharper

[2] Based upon a Rosiwal analysis by E. S. Larsen III. A chemical analysis of this rock is shown in column 2 and one of a similar rock in column 3 of Table 1.

outlines in the chilled phases and shows considerable resorption in the central parts of dikes where the groundmass and pseudoleucite are coarser-textured. Larsen observed that barium sanidine was not found in the rocks of coarsest texture, although many such rocks were studied. This he believed to be due to reworking of the sanidine in the rocks which crystallized slowly, with consequent redistribution of the celsian molecule through all the feldspar. The greater degree of resorption of the sanidine in the central portions of dikes is in accord with that hypothesis.

The pseudoleucite units are about 1 millimeter across in most specimens. Many of the rocks in which pseudoleucite could not be recognized in the hand specimen show fine pseudoleucite in the groundmass. Some leucite crystals show alteration around their margins and along cracks to a submicroscopic feathery intergrowth of minerals only slightly more birefracting than the leucite, but this material is believed to be the result of weathering and to be entirely different from the pseudoleucite composed of intergrowths of orthoclase and nepheline (?). The pseudoleucite varies considerably in texture and habit. Sanidine commonly extends inward from the margins of the pseudoleucite units. Toward the centers of the pseudoleucite units, especially in those which still contain a core of analcime, sanidine is usually bounded by well-defined crystal planes. Near the margin of the pseudoleucite the feldspar crystals interfere with one another and are commonly intergrown with altered nepheline. In some of the rocks the pseudoleucite is composed entirely of a fine feathery or plumose form of intergrowth between feldspar and nepheline (?). As the texture within the pseudoleucite becomes coarser the sanidine becomes better crystallized, and the outlines of pseudoleucite become less distinct; in many thin sections the minerals within the pseudoleucite merge with the groundmass, and no clear distinction can be made.

There is a tendency for the texture of the pseudoleucite to be coarser in the specimens which have coarser groundmass, and this is most readily observable by comparison of the chilled margins and the coarser central portions of dikes and sills. A particular study of this feature was made, and the results were included in a paper already published (Larsen and Buie, 1938).

A sill, 12 feet thick, on the high point of the ridge south of Lava Peak, at an elevation of 9050 feet, shows the effect of chilling very well. A section from about 10 inches from the base of the sill is made up of abundant crystals of augite, olivine partly altered to serpentine, and rather abundant grains of pseudoleucite about a millimeter across, all imbedded in an abundant groundmass that is fine-grained and contains small rods of pyroxene and some feldspar in an indistinct matrix. The pseudoleucite grains are rather coarse mixtures of feldspar and zeolite. A specimen from the middle of the sill has more and larger augite crystals than the specimen from near the base; it has about the same amount of olivine, now almost completely altered, and considerably more and larger pseudoleucite grains. The matrix is in smaller amount than in the rock from the base, is much more coarsely crystalline, and is made up of rather stout augite rods, much biotite in plates up to a millimeter long, sanidine up to 0.4 millimeter long, and some cloudy isotropic analcime (?). The grains of pseudoleucite are coarse, and each grain is made up of a few feldspar individuals intergrown with cloudy analcime (?). This indicates that on slow crystallization the texture was coarsened, more leucite phenocrysts and some coarse augite crystallized, the groundmass was not only coarsened but biotite was formed in abundance, probably with resorption of some olivine, and the pseudoleucite was coarsened in texture.

The large dike which forms a conspicuous ridge about 7 miles northwest of Geraldine and half a mile west of the road to Fort Benton was believed in the field

to be a composite dike with a dense rock (FBD 449), believed to be the first injection, next the walls and a coarser, micaceous rock (FBD 450), believed to be the second injection, in the center. A microscopic study of the rock next the walls shows it to be seriate porphyritic with abundant grains of augite up to a millimeter long and somewhat larger olivine grains in an abundant, very fine matrix made up of augite rods, magnetite, feldspar, analcime, and about 1 per cent of irregular biotite patches. There is probably some glass.

The center of the dike has more large augite crystals, no olivine, about 15 per cent of biotite in irregular plates up to a millimeter across, much sanidine in irregular elongated grains a millimeter long, and some cloudy analcime and zeolites. In addition to being much more coarsely crystalline than the border rock, it has biotite instead of olivine. This is the same difference as is found between the walls and centers of other dikes, and the border is probably a chilled part of the dike and not a separate intrusion.

Weed and Pirsson (1896, p. 187) describe a dike of leucite-sodalite-tinguaite 5 feet wide in which the pseudoleucite maintains its size to the very contact with the shales. The alteration to pseudoleucite has taken place to the very contact.

The rock (FBD 439) from a dike at the south side of the valley at Patterson's ranch house, half a mile east of Lost Lake, contains only about 10 per cent of pseudoleucite composed of a fine intergrowth of sanidine and altered nepheline (?), and over 50 per cent of millimeter tablets of feldspar which have margins with an index about 1.520 and cores whose index reaches that of balsam. This dike contains inclusions of feldspathic gneiss, and possibly the unusually high percentage of feldspar is attributable to assimilation of a considerable amount of such inclusions.

Order of crystallization.—Olivine apatite, much of the augite, leucite, and analcime, and some biotite crystallized before the magma became emplaced. With the exception of biotite, these minerals show essentially the same form and size in the chilled borders of dikes as in the central portions. Olivine ended its crystallization early, but augite continued to crystallize after emplacement as is shown by the presence of that mineral in the groundmass as thin prisms in the chilled borders and as thicker prisms in the central portions.

Pseudoleucite is grouped around the margins of augite crystals and to a less extent around the olivine. In many of the rocks leucite and analcime form phenocrysts and hence must have begun crystallizing early; also in most of them they continued to develop while the groundmass was crystallizing.

Barium sanidine is generally absent from the chilled borders and it may have crystallized very soon after emplacement. Sanidine is later than barium sanidine.

The weakly pleochroic biotite is intratelluric and was being resorbed rapidly at the time of injection. The small tablets of strongly pleochroic biotite crystallized entirely after injection. In the chilled borders of the dikes they are almost submicroscopic and can be recognized only because of their much darker color in one position. In the central

parts of dikes the tablets are usually from 0.1 to 0.2 mm. in diameter. The narrow border of darker biotite which is almost always present surrounding the pale biotite phenocyrsts has the same position in the sequence as the small tablets.

The opaque mineral, which for the most part if not entirely is magnetite, crystallized late; it is not included in the other minerals and some pairs of specimens show a marked difference between its grain size in the chilled borders and in the central portions of dikes.

The evidence in the dikes does not show conclusively whether the analcime and leucite were converted to pseudoleucite before or after the magma was intruded. If the breakdown occurred before, then the sanidine which was produced must have been recrystallized and coarsened in the pseudoleucite of the central portions of the dikes. Most of the nepheline (?) crystallized contemporaneously with the development of pseudoleucite.

The small amount of aegirite present is very late. The zeolites in the form of amygdules and those which replace feldspar in some specimens probably are hydrothermal. The fine-grained cloudy alteration product after nepheline (?) is probably hydrothermal. Some very fine-grained alteration product along cracks in the analcime probably results from weathering. Weathering is believed responsible for the formation of serpentine and iddingsite from olivine.

Reaction on olivine.—Many of the thin sections of olivine-bearing rocks show a peculiar replacement of this mineral. This is true of the augite and pseudoleucite mafic phonolites and of the biotite phonolite. A specimen (FBD 84) from a dike exposed on the ridge west of Smith Creek has 1-mm. grains of olivine in crude crystal form; around the margins and along cracks minute grains of magnetite are clustered together; surrounding the magnetite zone is a layer of brown biotite and around that a layer of green biotite which grades into the groundmass. Around some olivine crystals the biotite has coalesced to form crystalline units 0.3 mm. long. The replacement of olivine extends in along cracks, and lines of almost submicroscopic grains of magnetite and biotite have developed parallel to the long axis of the olivine crystals. Individual particles of biotite cannot be seen, but local areas of the olivine are brownish and show greater absorption in light vibrating parallel to these lines of replacing minerals. Some of the olivine grains are almost entirely replaced.

In the rock (FBD 268) of a dike which cuts Shonkin Sag laccolith olivine has been greatly attacked, and some grains are completely replaced by extremely fine magnetite.

Specimens from the central part of one of the chonoliths at the north edge of Shonkin Sag southeast of the Geraldine-Shonkin Creek road show more reaction of olivine to magnetite and biotite than a specimen taken from the chilled phase.

Another type of reaction was discovered in a dike of nonresistant rock exposed beside the road between Geraldine and Geyser about 0.2 mile north of Cottonwood Creek. The rock is of the mafic phonolite group and has large phenocrysts of augite and olivine and some ghosts of pseudoleucite that have coarse feldspar. The olivine is largely replaced and has a broad layer of fine augite grains next the olivine and beyond that a layer of pale green-brown biotite. Many of the olivine grains are completely replaced. In a dike which cuts the stock in Shonkin Creek, the reaction zones with successive magnetite, brown biotite, and green biotite are about the same in the chilled border, which has a submicroscopic groundmass, as in the center of the dike, which has a fairly coarse groundmass. That observation indicates that the reaction was intratelluric, but the difference between the chilled phase and the central rock of the chonoliths mentioned indicates that at least in some instances the reaction continued after emplacement.

BIOTITE PHONOLITE

Rocks of this type rank in abundance next to the augite and pseudoleucite mafic phonolite group, and they constitute about one-fourth of all the dikes of the Highwood Mountains area. They are the rocks referred to as minette by Pirsson (1905, p. 142-149). They show considerable variation both in texture and in the proportions of minerals. The color generally depends a great deal upon the extent to which the rock has been weathered, as the dark varieties become much lighter upon weathering. Perfectly fresh rock was found in none of the dikes of this type, and much of the petrographical study had to be made on badly altered material. Aside from the alteration, the rocks vary from light brownish gray to nearly black, as the ferromagnesian minerals especially pyroxene and olivine, increase. As the percentage of pyroxene increases, they grade into the augite mafic phonolite, and it has not been possible to draw consistently a sharp dividing line between the biotite phonolites and the micaceous varieties of the other group.

For convenience in description the biotite phonolites can be divided into three varieties. The variety which is most important quantitatively is intermediate in composition between the more felsic and the more mafic varieties. This intermediate variety is porphyritic with conspicuous phenocrysts of biotite 2 to 5 mm. in diameter set in an aphanitic groundmass which is darker in less altered specimens and light gray

in moderately weathered ones. A great many occurrences of this type of dike are found.

The principal variety of the biotite phonolites contains as phenocrysts about 10 per cent of biotite, 5 to 10 per cent of pyroxene, and as much as 5 per cent of olivine. The groundmass contains 40 to 50 per cent of feldspar, commonly as laths which attain a length of 0.5 mm. in a few specimens but which are much smaller in most. The feldspar shows only Carlsbad twins. It is in part sanidine but in some of the rocks it has indices near that of balsam indicating a considerable barium content. In the rocks having coarser feldspar there is up to 15 per cent of interstitial cloudy material believed to have been derived from nepheline. In some rocks the feldspar is in fine arborescent intergrowths with the altered nepheline (?); these intergrowths may be residual from pseudoleucite. The other minerals of the groundmass are 0.1 to 0.2 mm. tablets of biotite and prisms of pyroxene, together constituting 25-50 per cent of the rock, and about 1 per cent of opaque ore. Some of the thin sections show irregular streaks made up of coarser feldspar tablets, and analcime or calcite with a small amount of dark minerals. All these rocks have some secondary carbonate and chlorite.

No new analysis of this type of rock was obtained. The analysis of "minette" from a dike near Arrow Peak is quoted from Pirsson (1905, p. 145) in Table 1, column 1.

The more felsic variety of biotite phonolite is light brownish gray; some specimens are porphyritic, but the phenocrysts are fewer and less conspicuous than in the intermediate variety of biotite phonolite. This rock contains more feldspar and less biotite and olivine than the intermediate variety. Several dikes to the east and south of the mountains are formed of this rock, and a conspicuous example may be seen at the south edge of Shonkin Sag beside the County road between Geraldine and Geyser. In the dike are a great many inclusions of granitoid gneiss. The dike rock (FBD 404) contains no olivine. It contains 10 per cent of small prisms of diopside, for the most part under 0.1 mm. in length. In thin section one can see that these prisms are clustered together at many loci, and they obviously were formed as a result of reaction of the magma with the inclusions. It appears likely that the magma of this rock was markedly changed in composition by the assimilation of granitic material.

Another specimen of the felsic rock (FBD 505a), from a dike southeast of South Peak, near the north edge of sec. 9, T. 18 N., R. 9 E., has irregular cavities up to 4 cm. across, lined with quartz crystals. The quartz is in stubby prisms 2 mm. thick, with well-developed prisms and rhombohedrons. A thin section of the solid rock shows about 85 per cent of 0.5 mm. tablets of sanidine with 5 per cent of interstitial secondary carbonate, a few biotite tablets to 2 mm., a few per cent of olivine (?) now largely replaced by calcite, a small amount of opaque ore, but no quartz. The quartz crystals although they may be of hydrothermal origin appear to be genetically related to the igneous rock of the dike, and any occurrence of quartz in the Highwood igneous rocks is noteworthy.

The more mafic variety of the biotite phonolite differs from the other types in having more femag minerals, especially olivine and pyroxene. The rock of the several chonoliths at the north edge of Shonkin Sag a quarter of a mile southeast of the road from Geraldine to the upper part of Shonkin Creek contains about 10 per cent of 1 to 3 mm. phenocrysts of olivine, 40 per cent of pyroxene, and 15 per cent of biotite. The olivine shows some but not extensive reaction to form biotite (FBD 425, 426). It is surprising that so much olivine could remain, for these

chonoliths also contain inclusions of granitoid gneiss. In this rock the process of reaction of the magma upon olivine and upon the granitoid inclusions was arrested before it had proceeded nearly so far as in the dike described above.

Both the field observations and laboratory study indicate the following:

(1) That the biotite phonolite dikes all belong to one genetic type.

(2) That the great variation in percentages of certain minerals in the biotite phonolite dike rocks is in part due to assimilation of foreign rock.

SYENITE PORPHYRY

The rocks classed loosely under the name syenite porphyry constitute only a few per cent of the dikes. Their field relations indicate that they are the youngest of the injected bodies, and their petrographical character is in accord with this. Only a very few such dikes were found outside the mountainous terrain; a number of specimens were collected in the vicinity of Highwood Peak and south of it between Comb Butte and Arrow Peak.

The commonest type contains abundant phenocrysts of sanidine up to 3 mm. in length, and varying but small amounts of pyroxene and biotite phenocrysts. Sanidine as tablets less than 0.5 mm. long is the principal constituent of the groundmass. The pyroxene phenocrysts as a maximum constitute 15 per cent of the rock; biotite is subordinate. The pyroxene is for the most part augite, but the margins of phenocrysts in some of the rocks are aegirite; aegirite is also in the groundmass, making up 5 per cent of some of the rocks. The total of the dark minerals does not exceed 25 per cent. There is about 1 per cent of opaque ore and usually a small amount of apatite.

One specimen (FBH 831) contains tubular phenocrysts of feldspar 5 mm. long and slender prisms of green hornblende of similar size in a groundmass composed almost entirely of 0.5 mm. tablets of sanidine. The phenocrysts of feldspar all have indices higher than Canada balsam and are hyalophane or possibly oligoclase.

An unusual variety of syenite porphyry (FBD 504) was found in a 4-foot dike on the southwest slope of South Peak. It has about 20 per cent of large tablets of sanidine, some of which are 10 mm. across and 3 mm. thick, in a groundmass of 0.3 mm. tablets of sanidine. There is a little altered interstitial material and some secondary hematite, but feldspar constitutes 90 per cent or more of the rock. This probably is the rock Pirsson (1905, p. 136) referred to as syenite porphyry.

The rock of a conspicuous dike wall which crops out in the upper valley of the south fork of Highwood Creek was referred to by Pirsson (1905, p. 126-130) as tinguaite porphyry. A thin section of a specimen from this dike shows the felsic minerals of the rock to be considerably altered. Phenocrysts of feldspar, in 1 to 3 mm. tablets, constitute 40 per cent of the rock; it also has 5 per cent of augite prisms up to 1 mm. in length, and a smaller amount of biotite in 1 mm. tablets, as phenocrysts. Sanidine as 0.5 mm. tablets in the groundmass constitutes another 35 per cent of the rock; slender prisms of aegirite make 10 per cent, and interstitial

altered material which Pirsson concluded was possibly primary analcime makes 5 per cent. An analysis of rock from this dike is quoted from Pirsson in Table 1, column 8.

NEPHELINE SYENITE

Fresh nepheline is rare in the rocks of the Highwood area. The rock (FBD 88) from a dike on the ridge west of Smith Creek, below the junction of the north and south forks of Highwood Creek, is cut by a dike of biotite phonolite and in the general dike sequence may hold a place different from that of the dikes of syenite porphyry. It contains 20 per cent of pyroxene prisms up to 5 mm. in length, 40 per cent of sanidine, and 25 per cent of only slightly altered nepheline. Biotite, as 0.5 mm. tablets which are dark brown parallel to X and nearly opaque parallel to Y and Z, and some larger, paler tablets, constitutes the remainder. The central parts of each pyroxene phenocryst are augite, but there is a narrow border of aegirite around each.

A specimen of syenite from a sill 2 miles east of Geraldine is much like that just described, except that it has no nepheline but 10 per cent of interstitial zeolites which probably replace nepheline.

A dike at the top of Highwood Peak is a porphyritic rock with about 10 per cent of altered nepheline.

The sodalite solvsbergite, from a dike on the ridge between Middle and South peaks, described by Pirsson (1905, p. 121-124) has tablets of sanidine up to 10 millimeters in length and prisms of aegirite in a groundmass of aegirite needles and microlites of alkalic feldspar arranged in marked trachytic texture. In addition, there are dodecahedrons of melanite and some zeolitic material. From the analyses Pirsson concluded that the rock contained sodalite. The analysis and mode of Table 1, column 7, are quoted from Pirsson (1905, p. 123).

MONZONITE

Monzonites, as well as other rocks carrying plagioclase, are rare in the later volcanic series. A dike of monzonite porphyry near Thane Mountain has about 20 per cent thin tablets of oligoclase-andesine up to 5 millimeters in length, 7 per cent of augite, 10 per cent of green hornblende, and a little biotite in a groundmass which is made up of stout orthoclase tablets, 0.2 millimeter long, and a trace of quartz.

A dike north of Highwood Peak consists of rock that carries 15 per cent of phenocrysts of andesine in a groundmass which is 0.1 to 0.5 millimeter grained and made up of orthoclase, oligoclase, and a few per cent of interstitial quartz. Pyroxene and biotite each constitute about 5 per cent of the rock. The pryoxene is in very small grains that are collected in bunches or in seams that cross the rock. The pale biotite is also in seams.

A dike southwest of Arnoux Peak is made up mostly of millimeter-sized oligoclase grains and a little biotite and augite in a finer matrix of oligoclase and orthoclase.

A dike from the ridge south of White Wolf Creek, cutting the stock, is much like the mafic phonolites but it contains 10 per cent of labradorite tablets up to a millimeter in length.

CHONOLITHS OF BIOTITE PHONOLITE

At several places in the Highwood area irregular discordant bodies of a mafic variety of biotite phonolite are intrusive into the sedimentary strata. Some of these chonoliths contain abundant inclusions of sandstone, shale, gneiss, and igneous rock similar to that of the augite mafic phonolite dikes.

A group of three such bodies is exposed at the north edge of Shonkin Sag and southeast of the road between Geraldine and upper Shonkin Creek, near the southwest corner of sec. 14, T. 21 N., R. 10 E. The smallest of the three is about 100 feet in diameter; the largest is about 300 by 600 feet. The sandstone into which the biotite phonolite was intruded is much brecciated and strongly metamorphosed immediately adjacent to the contact. Numerous inclusions of coarse-grained, granitoid gneiss are present in the igneous rock.

About 0.7 mile west of Shonkin Creek and 0.5 mile south of the railroad, near the southwest corner of sec. 4, T. 21 N., R. 9 E., several small irregular-shaped bodies of biotite phonolite are intrusive into sandstone. The biotite phonolite is much brecciated and contains 20 to 30 per cent of rounded to subangular inclusions of shale, sandstone, and augite mafic phonolite.

A poorly exposed body near the southwest corner of sec. 23, T. 21 N., R. 8 E., in the drainage of Kiester Creek, is similar to those just described except that the inclusions make up nearly 50 per cent of the rock.

A striking group of biotite phonolite chonoliths is exposed near Coal-Mine Coulee, on the west edge of Shonkin Sag 1½ miles northwest of the place where the road from Geraldine to upper Shonkin Creek crosses the Sag. The shape and topographic expression of the bodies are shown in Figure 3. The Coal-Mine Coulee locality was studied also by Mr. David Griggs, who has kindly furnished much of the following information.

Chonoliths B and C form the most distinctive knobs, and they together with A are different from the others in that they are relatively free of inclusions. Chonolith C is shown in the foreground, and F in the background in Figure 1 of Plate 3. The jointing of B flares out at the base in a manner similar to that of Devil's Tower, as is shown in Figure 3 of

Plate 3. The jointing in chonolith C is similar but less well developed than in B. Downward-flaring joints are commonly found in bodies thought to be necks, and Hunt (1938) has suggested the mechanism of

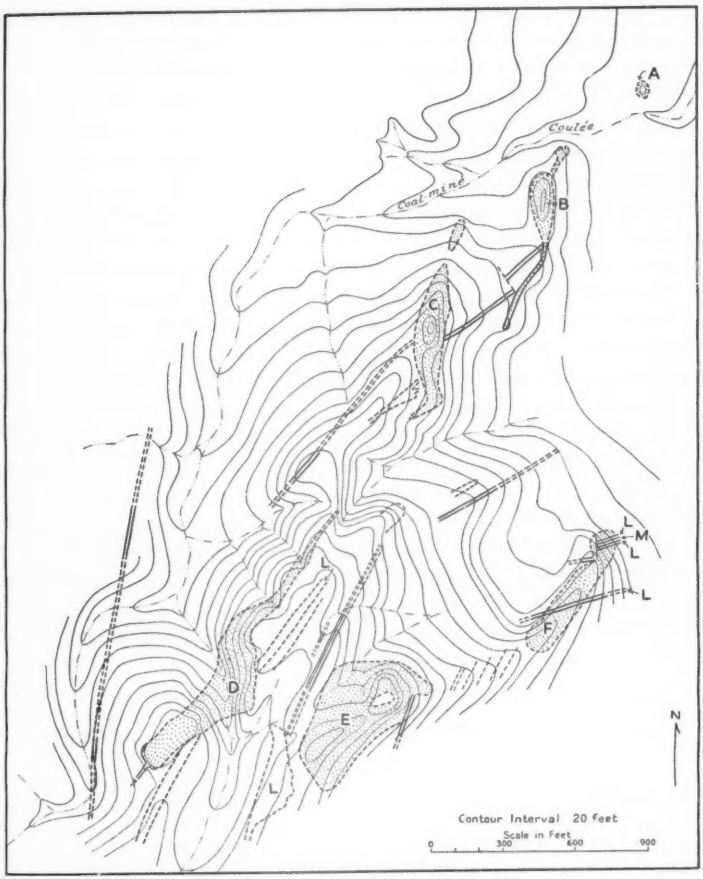


FIGURE 3.—*Map of intrusive rocks near Coal-Mine Coulee*

their formation. Chonoliths D, E, and F are remarkable for the abundance of inclusions in the biotite phonolite, which give the rock the appearance of an agglomerate. The inclusions are chiefly quartzite and gneiss; inclusions of mafic phonolite resembling the Tertiary eruptive rocks of

the region are less common. The matrix is in many places thoroughly macerated rock, the original character of which cannot be readily determined. The typical igneous rock of the chonoliths is a mafic variety of biotite phonolite, containing abundant large phenocrysts of biotite.

The linear arrangement of the chonoliths and the distributed nature of the sedimentary strata in this vicinity suggest that the intrusions may have occurred along a fault zone trending approximately north.

The origin of the rounded boulders of foreign rocks (Pl. 3, fig. 2), is uncertain. The possible explanation that they are boulders which dropped into open crates from glacial or Tertiary gravels seems unlikely, inasmuch as the most abundant inclusions are of rock types not readily available in any of the numerous bench remnants still prevalent in the Highwood area. The origin of the rounded inclusions at Coal-Mine Coulee is probably the same as that of the inclusions found generally in the Highwood area in other chonoliths and in dikes. A favored explanation is that the inclusions represent blocks of older rock engulfed by the rising magma and either brought up or floated up to their present positions. Rounding of the inclusions could have been accomplished by three, and possibly other, methods: (1) mechanical abrasion during ascent by grinding together in a viscous magma, (2) thermal exfoliation upon immersion in the hot magma. Laboratory experiments by Griggs and Dane have shown that when quartzite is immersed in a liquid hotter than the inversion temperature of quartz exfoliation is prominent. (3) reaction between the inclusions and the magma; the angular corners would be more rapidly attacked because of their greater ratio of surface to volume. Better opportunity for study of the effect of the magma upon inclusions was afforded in some of the dikes, and in these reaction is known to have occurred to a considerable degree.

HEADED DIKE:
A PECULIAR FORM OF DIFFERENTIATED IGNEOUS INTRUSION

DEFINITION

An unusual, intrusive, dikelike body was found on the east flank of the Highwood Mountains, about 8 miles southwest of the town of Geraldine. It was first observed in a small road cut where the county road from Geraldine to Geyser crosses the ridge which marks the location of this body. Preliminary descriptions have been given previously (Larsen and others, 1935, p. 290; Buie, 1936). In plan, the body is linear and closely resembles a dike; in cross section it is bulbous and much like a laccolith. It might be considered as a greatly elongated laccolith or as a dike which attains a greatly widened transverse dimension where it terminates upward. The broad, domal to flat top is concordant with the

sandstone into which the body is intrusive, and the lower portion becomes markedly constricted downward to a feeder dike. The form of this wider portion above the comparatively narrow feeder suggests the head of a steel railroad rail which rests upon the thinner web of the rail. Hence the body is called a headed dike.

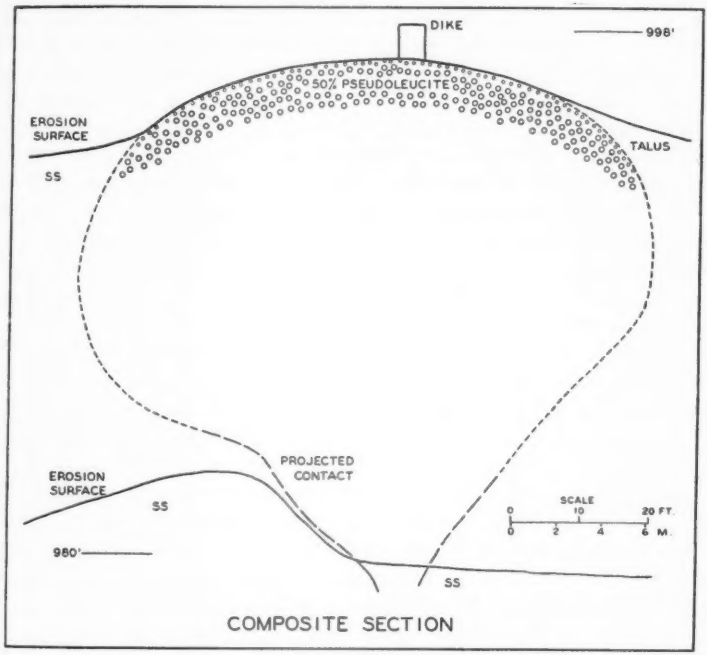


FIGURE 4.—*Composite cross section of the headed dike*
Fergusite layer at top, shonkinite below.

GENERAL DESCRIPTION

The maximum width of the headed dike, where fully exposed, is about 140 feet. The cross-sectional form, as interpreted from several incomplete sections, is represented in Figure 4. The strike of the body is roughly east. It is exposed intermittently through a distance of a little over 3 miles, but this does not represent its total length. To the west it strikes into the slopes rising to the mountains and to the east it extends under a high bench. At both ends of the exposures the cross sections are comparable to those elsewhere and, although there is some variation

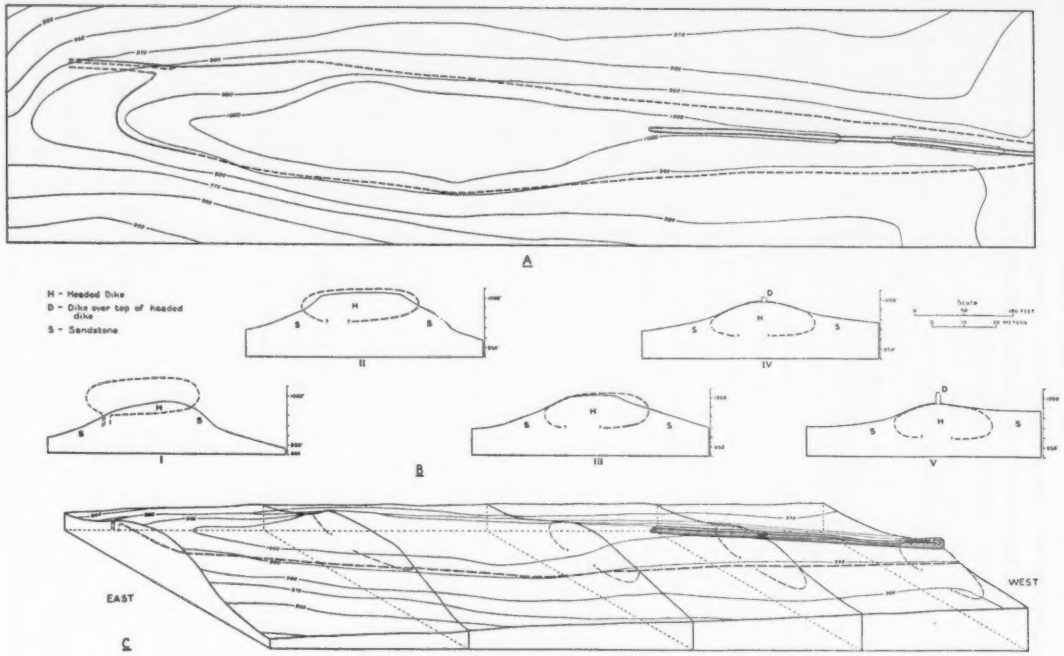


FIGURE 5.—*Details of headed dike near exposure 4 of Plate 4*

A. Enlarged map of area near a; B. Five cross sections; C. Isometric drawing.

in the form and dimensions, the general character of the body remains the same throughout. A map of the body is shown in Plate 4. The index map of this plate also shows the location of another exposure which may be an eastward continuation of the headed dike.

In general, the headed dike is well exposed. In several places, notably for about 0.8 mile west and about 0.1 mile east of the County road, though not exposed, it can be followed by the course of a dike with which it is known to be associated and by the anticlinal ridge produced in the sandstone. The longitudinal profile of the headed dike is not everywhere horizontal, and by walking eastward from the County road one can follow along a nearly horizontal ridge of sandstone until the upper surface of the body emerges. Continuing eastward, one passes from the dike which rests on top of the headed dike downward through the main body to the feeder dike below, in a horizontal distance of 500 feet.

From a portion of the geologic map of the headed dike five cross sections of the exposure just described were drawn, and an isometric drawing was constructed. These are shown in Figure 5. The drawing is made on the basis of a view from the north, inasmuch as the exposure of the headed dike at this place is better on the north side. To sketch in the hypothetical upper part of the eastern sections the top contact was projected eastward from the western end of the exposure. From the eastern end of the exposure the bottom contact was projected westward, at the angle of its dip, into the several sections. The reliability of each section depends largely upon the distance which the contacts were projected.

The dikelike appearance, the slightly curved plan, the rounded top, and the characteristic topographic ridge of the headed dikes are shown (Pl. 5, fig. 1). In the eastern exposure, the top is flat and the sides steep (Pl. 5, fig. 2). The western exposure is shown in Plate 6; the actual top of the headed dike and the cross sectional form of its upper part are recognizable. A dike cuts the sandstone above the headed dike and is cut off by the headed dike below (Pl. 5, fig. 3).

STRUCTURAL FEATURES

The relationship between the top of the headed dike and the sandstone is well shown in the small road cut where the County road crosses the ridge (exposure 3 on Plate 4). Here, as in other places, the sandstone beds are arched over the curved top of the igneous rock, and the contact is concordant. The nature of the contact at the sides of the body generally is not so clear, largely because metamorphism has obscured the bedding in the sandstone. Where the walls are nearly vertical, as in the mid-part of exposure 9, the contact at the sides appears to be, and in fact must be, discordant.

The dike which cuts the sandstone above the headed dike is from 5 to 15 feet wide, the widest portion being in the most westerly exposure. It can be recognized as older than the headed dike, because it ends abruptly against the top of that body and has dikelets of rock peculiar to the upper portion of the headed dike extending into it. The dike is broken by numerous faults having displacements of a few feet. Although not everywhere traceable, the dike probably is present above the headed dike in all those places where it has not been eroded away. In much of its course the dike is of about the same resistance as the slightly metamorphosed sandstone and can be followed only by the difference in vegetation. In the course of the field mapping only those features which could be definitely traced were plotted; later, after the form and structural relationships of the dike and headed dike had been determined, the dike was extended on the map in the form of a broken line in those places where it must occur but where it was not recognized in the field.

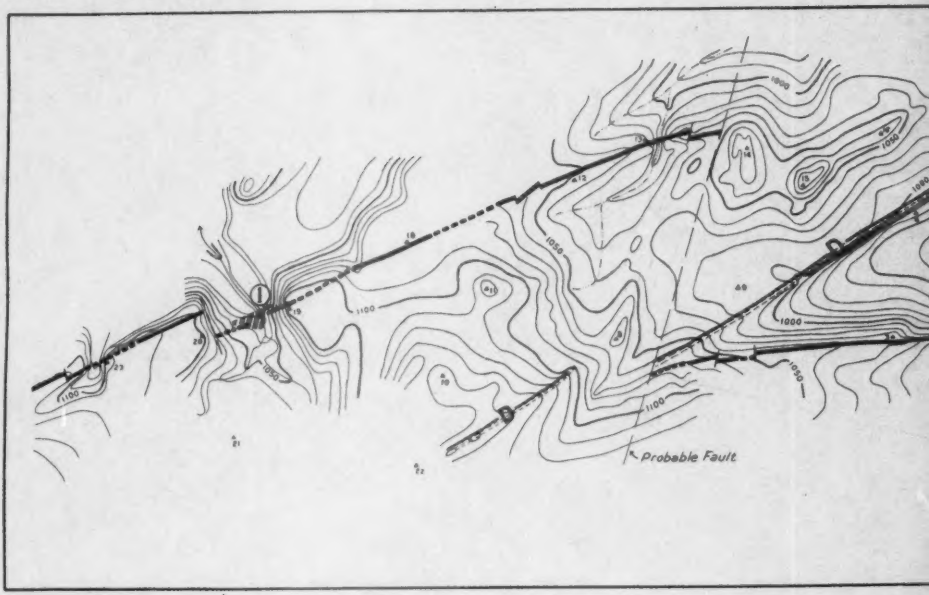
In addition to the very minor faults cutting the dike, there are several faults which cut both the sedimentary and the igneous rocks, producing vertical displacements of a few tens of feet. Two faulted and tilted segments are shown in Figure 4 of Plate 5.

In no place has a single vertical exposure, from sedimentary rock and dike above through the headed dike downward to the feeder dike below, been found, but the several vertically exposed partial sections, and the positions of the contacts as traced down sloping valley walls, reveal the following features:

(1) The body has a roof of sedimentary beds.
(2) Its transverse horizontal dimension rapidly increases downward until the maximum width is reached.
(3) Below the widest part the width diminishes and passes into a feeder dike.

A close approach to a complete vertical section is observable at the western end of exposure 5. At this place in a small saddle near the top of the ridge a remnant of sandstone rests upon the type of rock peculiar to the top of the headed dike, and only 80 feet away a gulch which cuts through the ridge exposes the lower portion of the headed dike where it has narrowed to less than 10 feet in width. These relationships are shown approximately in Figure 6.

In an attempt to determine whether the sandstone might at some place continue completely underneath the headed dike the natural exposures were supplemented by several trenches cut across the constricted portion of the igneous rock. No such continuation of the sandstone was found.


1050
1000
1100
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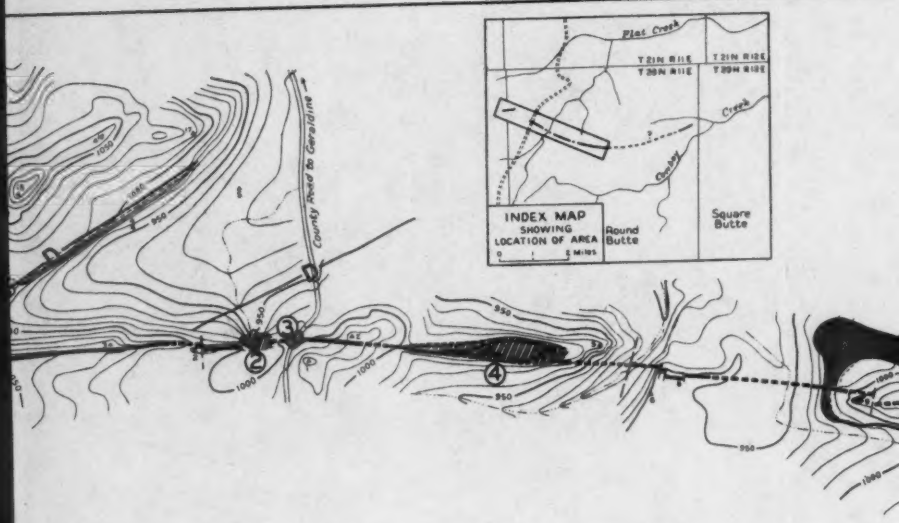
Probable Fault


Flat Creek
T 21N R 11E
T 20N R 11E
T 21N R 12E
T 20N R 12E
Creek
County
INDEX MAP
SHOWING
LOCATION OF AREA
Round Butte
Square Butte
0 1 5 MILES
County Road to Geraldine
1000
950
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
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2250
2300
2350
2400
2450
2500
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2600
2650
2700
2750
2800
2850
2900
2950
3000

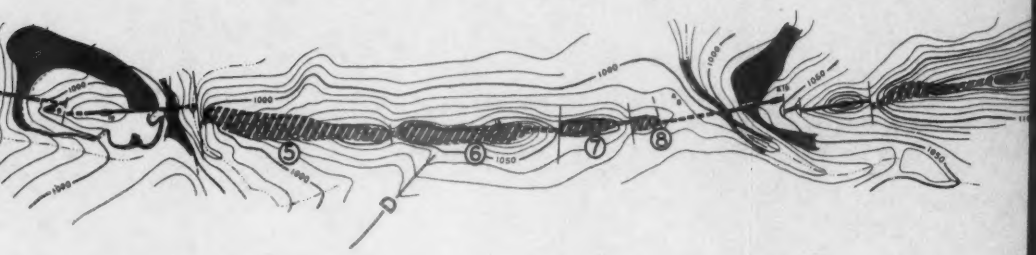
HEADED DIKE

NW ¼ TOWNSHIP 20 NORTH, RANGE 11 EAST
EAST SIDE OF HIGHWOOD MOUNTAINS
MONTANA

LEGEND

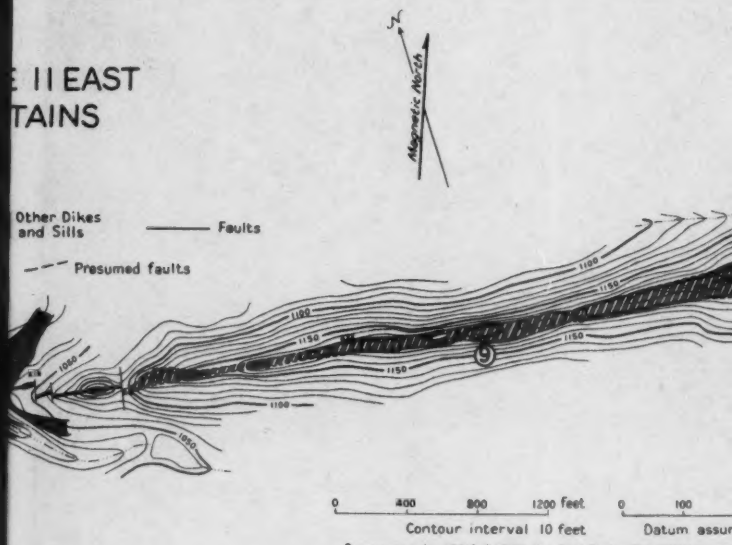
Headed Dike | Sandstone | --D— Dike above Headed Dike | Other Dikes and Sills | Faults

▲ Plane table stations | ⑥ Reference number for exposures | Presumed faults

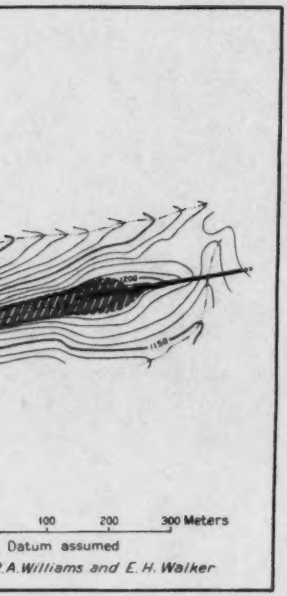


EADED DIKE

E II EAST
TAINS



Surveyed in 1934 & 1935 by B. F. Buie, R. A. Williams &


1200
1150
100
200
300 Meters
Datum assumed
A. Williams and E. H. Walker

Downward, the contacts between the sandstone and igneous rock become steeper and approach parallelism. The results of trenching at the western end of exposure 5 are shown in Figure 6. The south contact of the feeder at that place has been disturbed by post-intrusive faulting, but

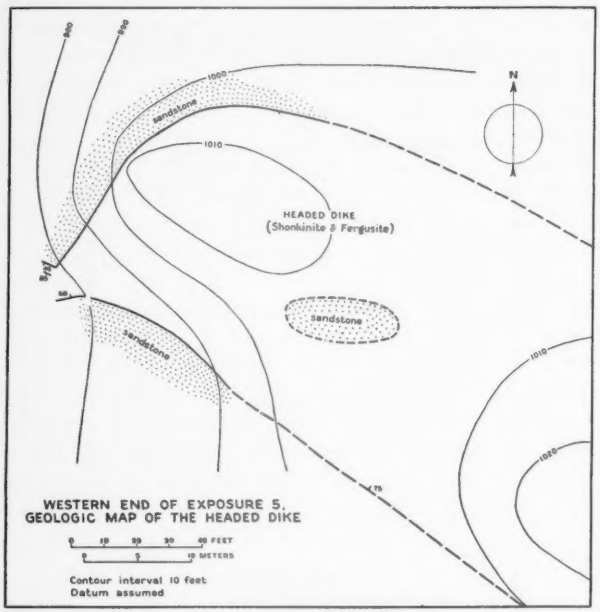


FIGURE 6.—*Details of western end of exposure 5 of Plate 4*
Strike and dip symbols are at the contact of sandstone and igneous rock of headed dike.

the north contact is in place, and there the dip increases from 40° to 85° in a horizontal distance of 2.5 feet.

The attitude of the contacts near the eastern end of exposure 5, as revealed by trenching, is shown in Figure 7. At the south side the contact dips north at an angle of about 25°. Trenching down along the contact at the north side showed that it dips at an angle of 30° for 1 foot, then flattens and continues irregularly downward so that at a distance of 4.1 feet from the starting point the contact is 1.5 feet below the level of the starting point. At 4.1 feet the dip steepens to 42°, and at a distance of 5.5 feet from the starting point the contact is 2.8 feet below that point. Excavation along the contact was not continued, but at 12.4 feet from the starting point, the original naturally exposed north

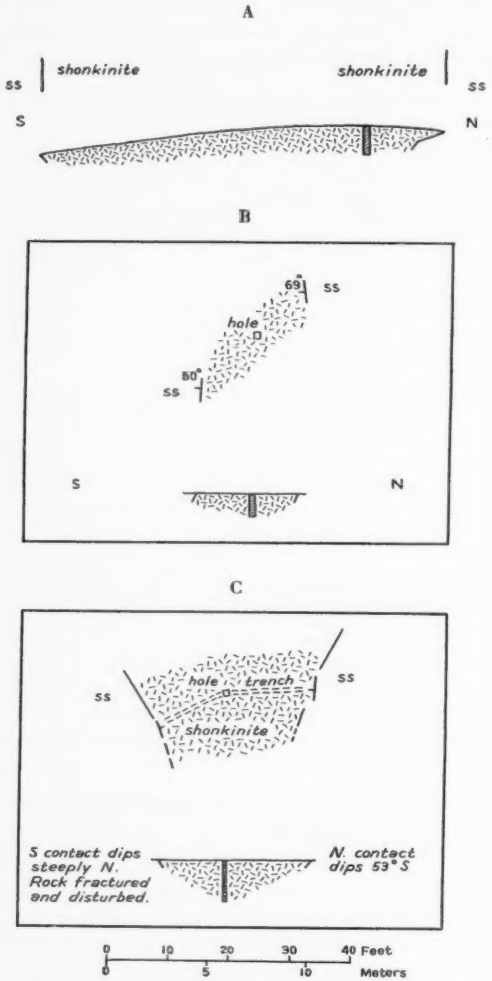


FIGURE 7.—*Cross sections of the headed dike showing the attitude of the contacts*

A. Near eastern end of exposure 5 (Pl. 4); B. Near eastern end of exposure 6 (Pl. 4); C. Near eastern end of exposure 7 (Pl. 4).

contact, a hole was dug and drilled to a depth of 4.5 feet below the starting point. This hole exposed only igneous rock.

Where exposure 6 becomes constricted near its eastern end the contacts were uncovered by trenching, and both dip southward. The north contact strikes N. 87 W. and dips 69° S.; the south contact strikes N. 74 W. and dips 80° S., as represented in Figure 7.

Midway between the contacts a pit was put down to a depth of 4 feet below the surface. From the bottom of this pit were obtained specimens of shonkinite, which included fragments of mafic phonolite like that of the dike above the headed dike. This relationship was puzzling until the feeder dike was studied where it is well exposed on the south side of the east end of exposure 4. (*See* Plate 4 and Figure 5.) At that place the shonkinite of the headed dike intrudes and includes fragments of a dike of mafic phonolite indistinguishable from the rock of the dike above the headed dike.

The relationships found by trenching at the eastern end of exposure 7 are shown in Figure 7. A trench 1.5 to 2 feet deep was dug from the southern to the northern contact; igneous rock of the type found elsewhere in the exposures of the lower part of the headed dike was uncovered. Because of considerable fracturing and weathering of both the igneous rock and the sandstone the south contact is not very well defined, but it appears to dip steeply to the north. The north contact dips 53° S. and strikes N. 85 E. A hole over 7 feet deep, 14 feet from the north contact, penetrated only igneous rock.

PETROGRAPHY

General considerations.—Although marked differentiation has taken place in the headed dike, as will be described later, the average composition of this body is very similar to that of the dike above and the feeder dike below. Considered in more detail, four principal types of igneous rock are recognized:

(1) Shonkinite, which constitutes the greater part of the body.
(2) Fergusite, which is a lighter differentiate occurring in the uppermost 4 feet. (*See* Figure 4.)
(3) Fine-grained mafic phonolite or fine-grained shonkinite, occurring as the dike above.
(4) Syenite, as small dikes and stringers through the other igneous rocks and occasionally extending a few inches into the adjacent sandstone.

Shonkinite.—The proportion of heavy to light minerals increases downward noticeably for 10 to 20 feet below the top of the headed dike. A

specimen (FBD 317) from 20 feet below the top at exposure 1, gives by a Rosiwal analysis the composition indicated in column 1 of Table 2.

In thin section the augite of the skonkinite is nearly colorless, nonpleochroic, and very weakly zoned. In the lower part of the headed

TABLE 2.—*Mineral composition of rocks of the headed dike*

(In per cent)

	1		2		3	
	Vol.	Wt.	Vol.	Wt.	Vol.	Wt.
Pseudoleucite	.....	.....	55	51	.....	.....
Sanidine	.....	.....	34	.....	.....	.....
Isotropic	.....	.....	21	.....	.....	.....
Sanidine	34	29	25	24	50	42
Zeolites from nepheline (?)	18	14	5	5	2	2
Augite	38	44	10	13	40	46
Olivine	3	4	2	3	3	3
Biotite	3	3	1	1	3	3
Magnetite	3	5	1	2	2	3
Apatite	1	1	1	1	1	1
Total	100	100	100	100	101	100

1. Shonkinite, 20 feet below top.
2. Fergusite of upper part.
3. Mafic phonolite of dike above headed dike.

dike it is euhedral to subhedral, whereas toward the top the crystal shape becomes less well defined, and the augite is much embayed by feldspar and nepheline (?) of the groundmass. The thin section of a specimen (FBD 321) from 6 feet below the top shows isolated patches of augite in optical continuity but separated by light minerals. The ends and edges of some of the augite grains show a slight alteration to light greenish-brown or dark-green hornblende. Sanidine and isotropic material are closely associated in the shonkinite. The sanidine occurs as prisms with cloudy isotropic material filling the spaces between, or as wormlike intergrowths with the cloudy isotropic material. In the lower part of the body the feldspar and isotropic material are interstitial to the euhedral augite prisms but approaching the top the feldspar becomes more definitely arranged in radia aggregates and clusters and in association with the isotropic material grades imperceptibly into the pseudoleucite of the fergusite in the uppermost part of the headed dike. At a distance of 4 feet below the top of the body, at exposure 1, pseudoleucite becomes definitely recognizable in the hand specimen. The amorphous material characteristically is cloudy and locally shows weak birefrin-

FIGURE 1. LOOKING EAST FROM EAST SLOPE OF KNOLL ON EXPOSURE 7 (Pl. 4)
Shows rounded top of portion of headed dike that dips toward the camera. Ridge of headed dike in the distance.

FIGURE 2. LOOKING EAST ALONG THE TOP OF EXPOSURE 9
Shows the flat top and steep sides.

FIGURE 3. NEAR VIEW OF WEST END OF EXPOSURES OF HEADED DIKE
Showing the dike above the headed dikes.

FIGURE 4. VIEW FROM NORTH
Showing faulted and tilted segments of the headed dike.

VIEWS OF HEADED DIKE

FIGURE 1. TOP AND CROSS SECTION OF THE UPPER PART

FIGURE 2. CROSS SECTION OF THE UPPER PART

WESTERMOST EXPOSURE OF HEADED DIKE (EXPOSURE 1)

gence. Olivine occurs as irregular anhedral grains within the outer portion of the augite prisms and as independent anhedral to subhedral grains. Along cracks and margins of some olivine grains there is frequently found an alteration product, probably serpentine. In size the olivine grains are variable; a few attain a length of 3 millimeters, but most are smaller. Biotite is not an abundant constituent in any of the shonkinite of the headed dike and it diminishes in quantity upward. Its characteristic occurrence is as small, intensely pleochroic tablets along the margins of the olivine grains and scattered throughout the groundmass. Magnetite occurs as irregular grains up to 0.4 millimeter in diameter. It is in part associated with biotite but is also included in augite and scattered through the groundmass. Apatite occurs mostly as inclusions in the augite and olivine but some is present in the groundmass.

The sequence of crystallization of the minerals in the shonkinite is believed to be as follows:

(1) Olivine: Irregular grains, largely resorbed before augite crystals ceased growing.
(2) Augite: Grew around grains of olivine.
(3) Leucite or analcime: (May be contemporaneous with augite) Later altered to pseudoleucite and almost completely resorbed.
(4) Sanidine: Crystallized in groundmass and in pseudoleucite.
(5) Nepheline (?) (cloudy isotropic material): Fills in between sanidine grains.

—— Biotite was after olivine, and probably before sanidine.
—— Magnetite may be early in the sequence or it may be a late replacement product.
—— Hornblende is very late-stage magmatic, or later.

Fergusite (pseudoleucite mafic syenite).—The leucocratic rock which forms the uppermost part of the headed dike contains approximately 50 per cent of pseudoleucite as well-defined conspicuous trapezehedrons, set in a matrix of finer grains of which only augite is recognizable in the hand specimen. This rock is very light in color and is less dense than any of the shonkinite. Where smooth erosion surfaces have been developed on this rock it presents a peculiar appearance, illustrated in Plate 2. Seen in the hand specimen it has a distinctly porphyritic appearance, with areas of pseudoleucite up to 8 millimeters, and occasionally 10 millimeters, in diameter. Close observation of a smooth surface reveals that each trapezohedron has a rim different from the core. The rock is too coarse for Rosiwal measurements but linear measurements were made on several specimens ground to plane surfaces, and gave by volume 48 per cent of pseudoleucite. This value for the

proportion of pseudoleucite is a minimum because there is some fine pseudoleucite which could not be clearly distinguished from the other minerals.

Under the microscope the pseudoleucite is recognizable as areas devoid of dark minerals, but the definiteness of its outlines is lost. The outer layer of the pseudoleucite for a thickness of about a millimeter consists of radiating clusters of sanidine prisms 1 mm. long with little interstitial isotropic material, and the central part of a fine-grained intergrowth of sanidine and isotropic material and zeolites. Much of the material referred to as questionable or altered nepheline is now a mat of fine prisms of a moderately birefringent zeolite, and some in the centers of the pseudoleucite areas is isotropic. It was estimated that the pseudoleucite areas occupy between 50 and 60 per cent of the thin section.

In addition to forming an important constituent of the pseudoleucite, sanidine comprises about half of the "matrix" between the pseudoleucite areas. The sanidine of the matrix is like that of the outer portions of the pseudoleucite, except that it is more zeolitized along cracks and edges. The sanidine shows Carlsbad twins, and some prisms are zoned, the central part having a higher refractive index and containing some barium. The optic angle is small. In the matrix, all the mineral which may have been nepheline is now a cloudy fibrous material having low birefringence.

Optically, the augite is like that of the shonkinite. In the fergusite it is much corroded and embayed by the light minerals and is mostly irregular fragmentary grains, 0.1 to 0.2 mm. in length, but some are 3 mm. long. Olivine, now largely altered to iddingsite, is present as small grains around or just within the borders of the grains of augite and as independent grains up to 0.5 mm. in diameter. Intensely pleochroic biotite occurs as irregular embayed masses and irregular specks and shreds scattered through the areas between the pseudoleucites. Irregular grains of magnetite up to 0.3 mm. in diameter occur throughout the matrix, a few as inclusions in the augite, but none in the pseudoleucite. Stubby prisms of apatite are present, mostly as inclusions in the augite.

The mineral composition of the fergusite given in column 2 of Table 2 is based on estimates from the thin sections, heavy mineral separations, and the chemical analysis and is believed to represent the average fergusite of the headed dike.

Contact zone of fergusite.—The fergusite shows surprisingly little chilling or other change at and near the upper contact. For a centi-

meter or so the pseudoleucites are somewhat smaller than at a distance from the contact and they may be lesser in amount. A thin section across the contact collected from the top of the body at the County road has a thin film of fine biotite plates next the sandstone. Beyond that is a layer about a millimeter thick of the igneous rock made up chiefly of clear sanidine plates about a millimeter in length. It has a little interstitial calcite and coarse sericite and some altered mafic minerals. Beyond this layer the thin section shows 20 mm. (to the edge of the section) that is nearly half pseudoleucite in crystals from 3 to 6 mm. across. They have an outer zone a millimeter thick that is made up chiefly of sanidine in poorly formed plates a millimeter long with a little calcite, sericite, and cloudy analcime (?). The central part of the crystals is cloudy material cut by some thin seams of calcite and sericite. The matrix between the pseudoleucite crystals is nearly millimeter-grained and is made up chiefly of sanidine with considerable fine patches of biotite and some altered nepheline and calcite and a few small grains of altered pyroxene and olivine.

A specimen 5 centimeters below the top is much like that 2 centimeters below the top but it has more pyroxene prisms up to 3 millimeters in length, more olivine, coarser biotite, and more mafic minerals in the matrix. The cores of the pseudoleucite are a fine intergrowth of sanidine and zeolites.

A specimen 30 centimeters below the top has some well-defined pseudoleucite but has more mafic minerals than the specimen just described and approaches the shonkinites in composition.

A specimen from a meter below the top shows some pseudoleucites up to a centimeter across in the hand specimen but in a thin section it shows somewhat smaller and fewer and less-well-bounded pseudoleucites than the rock 30 centimeters below the top and has somewhat more femic minerals.

A specimen from 2 meters below the top is a dark, coarse-grained shonkinite that shows only indistinct pseudoleucite. At a somewhat greater distance from the top, little or no evidence of pseudoleucite remains.

A specimen from the ridge east of the County road shows the contact of the headed dike and the overlying dike. The latter is cut by several dikelets of fergusite from less than a centimeter to several centimeters across. The contacts are sharp, though the fergusite has included a few pyroxene crystals from the older dike. These dikelets are made up of closely packed pseudoleucites almost as large as those of the main fergusite body. The microscope shows that a dikelet 8 millimeters wide is made up of rather coarse intergrowths of sanidine and analcime with a

very little biotite and pyroxene. A dike 2 centimeters across looks like the fergusite of the main headed dike a few centimeters below the contact but may have a little less of the mafic minerals in the matrix between the large pseudoleucites.

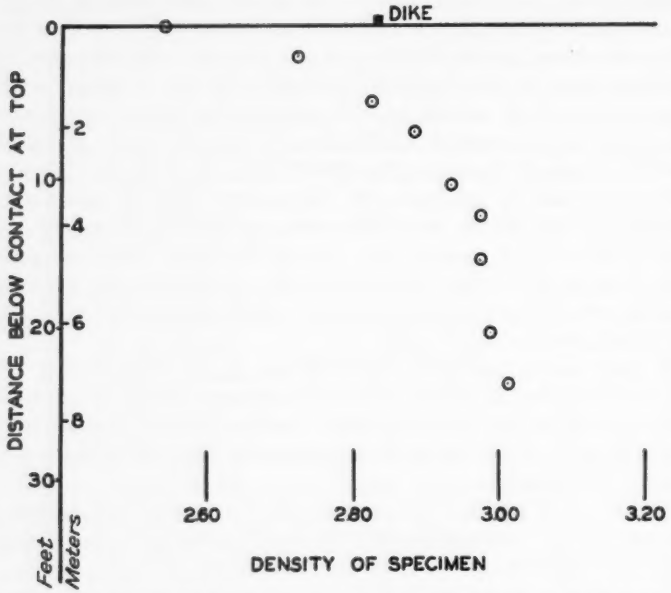


FIGURE 8.—*Density of hand specimens from a cross section of the headed dike*

Circles represent specimens from the headed dike. Solid square is mafic phonolite of dike above the headed dike.

To show quantitatively the change in composition in the rock of the headed dike from the upper contact to the main shonkinite, specific-gravity determinations were made on specimens from a composite section, believed to be typical, and are plotted in Figure 8. The variations in specific gravity are due chiefly to the variation in the proportion of mafic minerals in the rocks. The specific gravity of the dike above the headed dike is shown by a dark square.

Mafic phonolite of the dike above the headed dike.—The rock of the dike above the headed dike is medium-gray, holocrystalline mafic phonolite. The augite phenocrysts are prisms about 4 millimeters long and are considerably smaller than those of most of the dike rocks of the High-

wood Mountains area. In the hand specimen, in addition to augite, some cleavage surfaces of feldspar can be recognized. The rock is compact, brittle, and breaks with a subconchoidal fracture.

Augite is principally phenocrysts, as there is only an occasional grain as small as the grains of feldspar. The augite phenocrysts are subhedral and corroded along margins. They are twinned and weakly zoned, about like the augite of the headed dike.

Anhedral sanidine constitutes almost the entire groundmass. A small amount of cloudy, nearly isotropic material, probably derived from nepheline, is interstitial to the feldspar. There is about 3 per cent of olivine in grains up to about 1 mm. in diameter. It is altered along cracks to a light amber-yellow anisotropic material (iddingsite ?). Plates of strongly birefringent biotite and small grains of magnetite occur in the groundmass. Somewhat less than 1 per cent of apatite occurs as prisms in the groundmass and in the augite.

An estimate of the mineral composition, as made from the thin section, is shown in column 3 of Table 2.

Syenite.—The syenite, which occurs as dikelets or stringers within or very near the headed dike, is a very light-colored, holocrystalline rock. Needles of augite 1 centimeter in length, prisms of feldspar 5 millimeters to 1 centimeter long, and an occasional tablet of biotite about 5 millimeters in diameter can be observed in the hand specimen. Small cavities contain needles of clear, colorless natrolite.

About 85 to 90 percent of the rock is made up of sanidine. The interstitial space is filled chiefly by a moderately birefringent fibrous material, apparently an alteration product after nepheline. Locally, the sanidine is altered to this fibrous mineral.

Augite, bordered by green hornblende, and biotite and magnetite constitute the remainder of the section.

MAGMATIC DIFFERENTIATION

The shonkinite and fergusite of the headed dike are made up of the same minerals; the former is rich in the heavy minerals, the latter in the light. This strongly suggests crystals differentiation by gravity separation. Their differentiation may have taken place in a deep magma reservoir, and the two rocks have been injected successively, or the differentiation may have taken place in the headed dike itself. Some features of the headed dike which indicate that the differentiation occurred after emplacement are:

(1) The lighter fergusite is above the shonkinite.
(2) There is a textural gradation between the fergusite and the shonkinite.

(3) The specific gravity and per cent of heavy minerals gradually increase downward through the fergusite layer and into the shonkinite below.
(4) Apophyses of fergusite in shonkinite, or of shonkinite in fergusite, are lacking.
(5) The layer of fergusite conforms to the arched roof.

TABLE 3.—*Relationship between distance below contact at top of headed dike, specific gravity, and heavy and light mineral content*

Specimen number	Distance below contact at top (feet)	Specific gravity	Heavy minerals (per cent)	Light minerals (per cent)
324	0.0	2.54*		
323	1.0	2.72	33	67
322	4.0	2.82	46	54
321	6.0	2.88	50	50
320	9.5	2.93	59	41
319	11.5	2.97	62	38
318	14.5	2.97		
317	19.5	2.98	65	35
316	23.0	3.01	65	35

* Specific gravity of specimen 324 may be unduly low because of its slightly weathered condition.

The relative positions of the fergusite and the shonkinite are represented, approximately, in Figure 4. The fergusite extends up to the cover of sandstone, with only the uppermost half inch showing any effects of contact chilling. The recognition, in the field, of the gradation from fergusite into shonkinite is substantiated by the specific gravity and mineral ratio determinations. The relationship between density of hand specimens and the distance below the upper contact of the headed dike is shown by the points plotted in Figure 8. This same relationship and the correlation between specific gravity and amounts of heavy and light minerals are shown in Table 3.

The layer of fergusite makes up the top of the headed dike and extends down onto the upper part of its flanks. This conformation with the arched roof is not what would be expected if the fergusite and the shonkinite had been intruded successively; it is what would be expected from gravitative differentiation. Leucite rising in the magma would be trapped against the sloping upper surface and thus produce a downward extension of the fergusite layer onto the flanks.

The arcuate cross-sectional form of the layer of fergusite and the nearly consistent specific gravity of the shonkinite downward from 12 feet below the top contact indicate that floating of leucite was the

dominant factor in causing differentiation. However, this evidence is inconclusive, and sinking of augite may have been an important, or even the dominant, factor. The trapezohedrons of pseudoleucite in the headed dike are larger than those found in any other of the Highwood rocks. Their large size would have facilitated their rising through the magma. The presence of smaller leucitohedrons against the sandstone at the top of the headed dike indicates that the original leucite or analcime crystallized, or at least that the crystals continued to grow, after emplacement of the magma.

Though unusual in natural occurrence, gravitative differentiation by floating of crystals has been reported by several investigators of silicate melts. Bowen (1915, p. 175-191) gives an account of the floating of tridymite in a melt consisting of 85 per cent pyroxene (diopside: Mg_2SiO_3::75:25) and 15 per cent silica. Neubauer (1911, p. 197-205) describes a remarkable example of floating of leucite, which occurred in a melt consisting of 60 per cent leucite, 25 per cent augite, and 15 per cent orthoclase. More and larger leucite crystals were found in the upper half of the melt, and some small parts were almost exclusively leucite.

If the leucite (or analcime) crystals continued to grow after emplacement of the headed dike magma, as they apparently did, the breakdown to pseudoleucite must have occurred also after emplacement. Whether they broke down before, during, or after the gravitative separation is not known. The zeolites associated with some of the pseudoleucite probably are entirely secondary.

The dikelets and stringers of syenite in and near the shonkinite appear to be from a late-stage differentiate or residual magma. This rock has no direct bearing upon the more pronounced shonkinite-fergusite differentiation of the headed dike.

POSSIBLE EASTWARD CONTINUATION OF THE HEADED DIKE

Two miles east of the easternmost exposure represented in Plate 4 the drainage of Cowboy Creek has cut into the benchland and exposed a body of rock petrographically similar to that constituting the headed dike. The total length of this exposure is about 0.4 mile. It strikes S. 70° – 75° W. and by projection under the bench to the west would meet the curved line of exposures which are present on the west side of the bench. To the east it is interrupted by faulting. The top of the body can be observed along the trail, and sandstone over the igneous rock is clearly visible. However, the form is not so regular here as in the area mapped on the west side of the bench. Locally the top is flat, but generally the body is parted longitudinally by a wedge of highly

metamorphosed sandstone which extends downward from the top. Near the eastern end of this exposure the south contact of the body is exposed, and here beds of sandstone and shaly sandstone abut against a vertical contact with the igneous rock. A short distance to the west, however, the contact dips beneath the igneous rock. The rock of this body is an uncommon variety of augite-pseudoleucite mafic phonolite, strikingly similar to that of the typical exposures of the headed dike. Also present are stringers of light-colored syenitic rock similar to, though narrower than, the syenite stringers of the headed dike. The only suggestion of gravitative differentiation is the presence of a concentration of zeolites in the upper part of the igneous rock. This exposure differs from the typical exposures of the headed dike in: (1) having smaller dimensions, both in width and in vertical thickness of the widened portion; (2) having a more irregular form; and (3) lacking well-defined evidence of gravitative differentiation.

COMPARISON WITH OTHER INTRUSIVE BODIES

Washburne (1933) has briefly described intrusive bodies from Oregon which closely resemble the headed dike. Detailed descriptions of the bodies observed by Washburne have not been published, but in conversation with the writer he emphasized the importance of (1) steeply inclined or vertical fractures in sedimentary beds, (2) the intrusion of igneous rock along these fractures, (3) the constricted form of the lower part of the igneous body, and (4) the longitudinal conformation of the top with the dip slope of the slightly tilted strata.

Consideration was given to the idea that the headed dike might represent on a much larger scale the type of intrusion referred to by Daly (1933, p. 89-90) as a ribbon injection. In a summary description Daly states:

> "The name ribbon injection has been given to long, thin, narrow apophyses of red rock from the differentiated sill at Pigeon Point, Minnesota. The ribbons are in general like flat nails driven into the metargillite country rock, with the flat side of the nail in the plane of the bedding. Laterally the nails sharply truncate the bedding. The maximum length observed was several meters; the maximum widths and thicknesses are measurable in millimeters."

Despite the great difference in size, one might be inclined to stress the comparison of the ribbon injections with the headed dike if the feeder of the headed dike were not present and visible in the field.

The descriptions of the Great Dike of southern Rhodesia (Wagner, 1915; Lightfoot, 1927) suggest that it may be a headed dike, much larger than the one here described. It is 300 miles long and several miles wide and is reported to have layers of norite, pyroxenite, serpentine, and other rocks. It intrudes granites and gneisses.

MECHANICS OF INTRUSION

The mechanics by which the headed dike was intruded offer some difficulties of interpretation. However, reasoning from the descriptive evidence presented above, there can be little doubt that the following events took place:

A dike of mafic magma was intruded into the flat-lying sandstone, probably along a fault. After this dike had become largely or completely crystallized, another magma only slightly different in composition invaded along the same fracture. At depth this subsequent intrusion produced, with the earlier dike, a composite or multiple dike structurally not unlike others found in the Highwood area. Nearer the surface, where the weight of overlying rock became appreciably less, the sandstone and the earlier dike held together and were bodily uplifted by the intrusive force of the invading magma. The magma spread to produce the bulbous cross-sectional form of the headed dike.

Two dike segments strike into the headed dike but do not cross it, and neither continues on the opposite side. This indicates that the headed dike and the dike which preceded it were intruded along a fault, but the evidence is not conclusive, for discontinuous dikes are not uncommon in the Highwood area.

It is doubtful whether the lateral spread of the magma of the headed dike after it rose along the vertical or steeply inclined fracture was favored by the presence of an intersecting horizontal fracture, as proposed by Washburne to account for the Oregon "still-dikes", for if such fracture had been present the dike which preceded the headed dike should have been diverted by it.

The augite phenocrysts in the headed dike, especially those in the lower part, are oriented with their long axes horizontal and parallel to the walls. There is some question as to what direction of movement of the magma would be required to produce such orientation, but it is probable that this movement was parallel to the long axes of the phenocrysts. In any event, the movement in the headed dike must have been of the same nature as that which occurred in many of the dikes of the Highwood area, for the dikes commonly have augite phenocrysts similarly oriented. Some variation in cross-sectional area of the headed dike is recognizable, and this variation would favor adjustment by horizontal movement along the strike. The orientation of the phenocrysts could have been produced by only a small amount of movement.

The fact that the chilled phase at the contact with the sandstone is not so conspicuous as it is in the laccoliths and in many of the dikes is attributed to movement of the headed dike magma during emplace-

ment. This movement is thought to have been of two sorts: (1) circulatory, caused by the forceful injection of the magma through a relatively narrow opening; and (2) longitudinal, caused by adjustments of the magma to fit the varying cross-sectional form as the country rock yielded nonuniformly. Mineralogically, the whole layer of fergusite at the top of the headed dike is a "chilled phase", for crystallization was too rapid for the pseudoleucite to be reworked to form coarse-grained nepheline syenite as in the laccoliths. Movement within the magma, especially circulatory movement, would have heated the country rock more rapidly and would also have distributed the effects of cooling through more of the igneous rock.

Judging from the altitude of the basal contact of the volcanics 2 or 3 miles to the west, the present position of the headed dike could not have been more than a few hundred feet below the surface at the time of intrusion. This is favorable, because the events suggested would have been facilitated by a shallow depth of intrusion.

A similarity to the laccolith intrusion is indicated by the fact that the headed dike intrudes the same formation as the laccoliths, which according to Reeves (1929, p. 165) is the Eagle sandstone.

SUMMARY OF THE HEADED DIKE

An intrusive, dikelike body, apparently different from any well-exposed body which has been fully described, is here described from the Highwood Mountains area of Montana. For this body, and for others of similar form and origin which may be found, the term headed dike is suggested. Although this body is relatively small—less than 200 feet in width and only a few miles in length—the same forces which controlled its intrusion and its form may have been operative during the intrusion of much larger bodies.

Two principal types of rock make up the headed dike: shonkinite and fergusite. Differentiation was gravitative after intrusion. Both floating of leucite and sinking of augite appear to have been operative.

The headed dike differs from the laccoliths in one important respect: It is smaller, and cooling of the whole body was accomplished before the leucite which became concentrated in the upper layer could be reworked to a granular nepheline syenite.

Intrusion was into nearly flat-lying Cretaceous sandstone probably only a few hundred feet below the surface. The top of the body is concordant with the bedding of the sandstone, but the sides appear to be discordant. The locus for the intrusion was determined at least in part by the presence of an earlier dike.

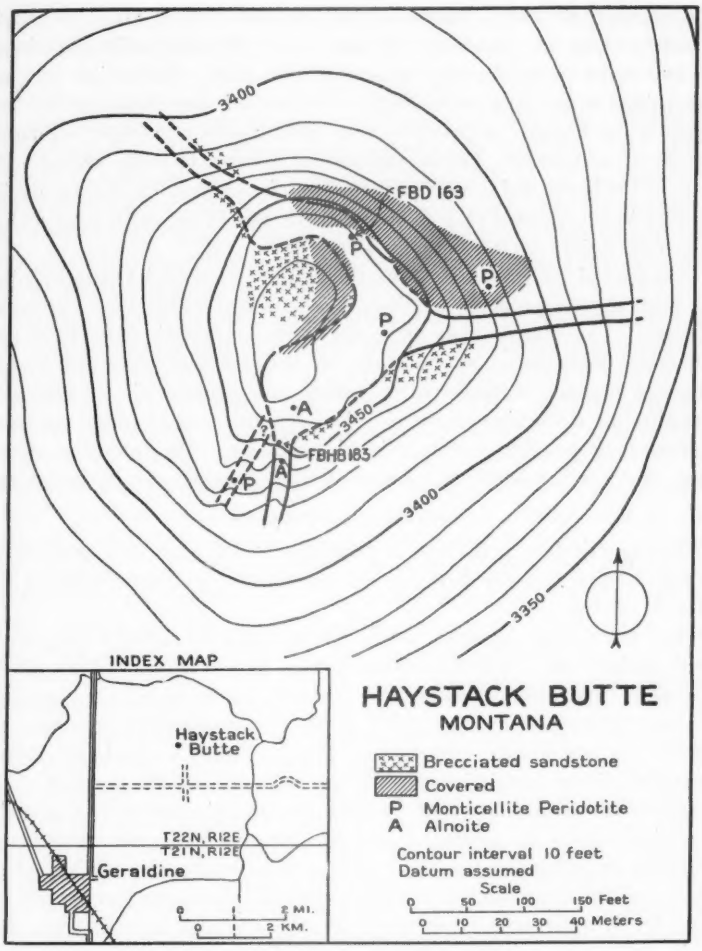


FIGURE 9.—*Geological map of Haystack Butte*

HAYSTACK BUTTE CHONOLITH AND OTHER MELILITE ROCKS

GENERAL CHARACTER

Haystack Butte, about 3 miles northeast of Geraldine, is a small hill rising about 150 feet above the nearly flat plain. It consists of metamorphosed Cretaceous sediments and a small chonolith. A plane-table map of the butte is shown in Figure 9. The sedimentary rocks about

the intrusive are much brecciated and metamorphosed, and these hard, resistant rocks are responsible for the butte. The chonolith is made up of two rocks so much alike magascopically that a distinction was not recognized in the field; accordingly, the detailed distribution of the two types is not known. A granular rock (monticellite peridotite) composed chiefly of monticellite, biotite, and olivine appears to make up the main part of the body, and a melilite-nepheline-biotite rock (nepheline alnoite or turjaite) was found only in the southern part of the main mass and in the eastern dike on the southern slopes of the hill.

The part of the Haystack Butte chonolith now exposed was intruded at no great depth—probably a few hundreds of feet rather than thousands of feet. The magma that gave rise to the chonolith must have had abundant mineralizers as evidenced by the unusually extensive hydrothermal contact metamorphism which has introduced feldspar and aegirite into the sediments over a wide zone and has deposited pyroxene between the fragments of brecciated sandstone. The extensive alteration of the minerals of the igneous rock is probably also hydrothermal.

MONTICELLITE PERIDOTITE

The monticellite peridotite is a dark greenish-gray rock with much coarse biotite, but the main part of the rock is millimeter-grained and rich in olivine.

The microscopic analyses show that the rock is rather even-grained with grains from 1 to 3 millimeters across. The rocks are rather uniform except for alteration, and the fresh rocks are made up for the most part of monticellite, biotite, and olivine, with a few per cent each of magnetite, perofskite, and apatite. Interstitial cloudy, sensibly isotropic amorphous material with a high index of refraction constitutes a few per cent. The monticellite carries scattered patches of isotropic amorphous material that is probably an alteration product. The biotite molds between and encloses poikilitically the other minerals, especially the olivine. It is pale and faintly pleochroic with the unusual absorption formula $X>Y$ and Z. The olivine is much resorbed and is enclosed in the biotite. One thin section shows a section through a rounded nodule 5 millimeters across made up of an aggregate of small olivine grains. The chilled variety from the westerly dike on the south slope has about 10 per cent of large rounded olivine phenocrysts partly altered to serpentine, embedded in a fine-grained aggregate of biotite, carbonate, and alteration products. In many of the specimens collected the olivine is largely altered to serpentine, and the monticellite to aggregates of a colorless fibrous mineral. There is much secondary calcite in some of the specimens. An analysis,

mode, and norm of a typical rock that shows only a moderate amount of alteration is given (Table 4, column 4).

NEPHELINE ALNOITE

The alnoite is a dark greenish-gray rock that looks like a minette. It is not so distinctly grained as the monticellite peridotite. Its texture varies in different parts of a single hand specimen. It contains much biotite, in plates up to several millimeters across, and some white minerals. Coarse-grained light-colored segregation streaks or lenses several millimeters wide contain much coarse biotite and a mixture of radiating fibers of pectolite, zeolites, and calcite.

In thin section the fresh alnoite is from 0.5 to 2 millimeter-grained and is made up nearly half of melilite, nearly a quarter each of biotite and nepheline, a small but variable amount of olivine, and a few per cent each of apatite, magnetite, and perofskite. The melilite is in thick tablets. It is optically negative and shows abnormal blue interference colors in the central part and higher colors in the outer skin. It is more or less altered to cebollite and other minerals. The biotite encloses the other minerals poikilitically and is filled with apatite needles. The olivine is rounded from resorption and is enclosed in biotite. The nepheline is interstitial. The apatite is much more abundant in the alnoite than in the monticellite rock. All the rocks are somewhat altered, and some greatly so. Carbonate, cebollite, serpentine, zeolites, and coarse radiating aggregates of pectolite are the chief alteration products. The order of crystallization was: olivine, resorption of olivine, apatite, melilite, perofskite, magnetite, nepheline, biotite, and some interstitial material.

A chemical analysis of the alnoite is shown in column 1 of Table 4. The rock is very high in BaO and P_2O_5.

A specimen of alnoite collected from the valley of Martin Creek is finer-grained and has more biotite than the rock from Haystack Butte. Pale biotite plates up to a millimeter across make up about 40 per cent of the rock. Melilite and nepheline, partly altered to zeolites, each make up about 25 per cent, apatite about 5 per cent, and perofskite, magnetite, and melanite each about 2 per cent. As usual in such rocks, the melanite is very late.

CHEMICAL PETROLOGY

Chemical analyses of the alnoite and of the monticellite peridotite have been made by F. A. Gonyer and are given in Table 4 together with analyses of similar rocks for comparison. The alnoite from Haystack Butte (column 1) is higher in Al_2O_3 and MgO and lower in Na_2O than the turjaite from Turja (column 2); it is higher in Al_2O_3 and lower in MgO and CaO than the alnoite from Isle Cadieux (column 3). The

alnoite from Haystack Butte has 1.26 per cent of BaO, which is unusually high for any rock. The monticellite peridotite (column 4) is much like the monticellite-rich alnoite from Isle Cadieux. Since none of the specimens of this rock examined contain melilite the name monticellite peridotite seems more appropriate than monticellite alnoite.

Mr. George Steiger of the United States Geological Survey kindly tested spectroscopically samples of the monticellite peridotite, the monticellite, and the turjaite from Haystack Butte, and specimens of alnoite from Isle Cadieux and Como, Quebec, and St. Moneque, Montreal, for silver, arsenic, boron, beryllium, bismuth, cadmium, germanium, lead, antimony, tin, and zinc. Tests were made by placing the material di-

TABLE 4.—*Analyses, norms, and modes of alnoites, monticellite peridotites, and related rocks*

	ANALYSES					
	1	2	3	4	5	6
SiO_2	32.20	34.72	31.10	33.70	30.85	33.26
TiO_2	2.27	3.31	2.73	2.18	2.87	2.15
Al_2O_3	15.45	12.19	10.08	6.08	8.21	5.90
Fe_2O_3	5.09	6.44	3.64	4.23	3.33	5.30
FeO	3.59	4.82	3.35	6.41	6.52	6.54
MnO	0.06	0.28	0.09	0.09	0.21	0.15
MgO	9.46	5.84	12.25	24.92	23.16	26.41
CaO	18.86	19.08	22.77	14.80	16.46	14.47
Na_2O	2.13	5.11	1.95	0.32	1.01	1.23
K_2O	3.66	3.05	3.56	2.10	1.43	0.82
H_2O-	0.28	0.17	0.46		0.05	0.09
H_2O+	4.02	2.13	0.76	3.81	1.22	1.91
CO_2	0.50	0.81	4.94	nd.	3.04	1.10
P_2O_5	1.08	1.88	2.01	0.72	1.90	0.76
S	0.08	0.17		0.06		
SO_3						0.22
BaO	1.26			0.13		0.08
SrO	0.10			0.06		
Cr_2O_3				0.12		0.05
ZrO						none
	100.09	100.00	99.69	99.73	100.26	100.44
	NORMS					
an	21.96	1.39		9.17		8.06
ne	9.66	23.28		1.42		5.68
ka	12.33			6.32		1.93
lc		13.95		.87		
di		11.23				
ol	16.66	6.58		47.08		49.56
cs	19.78	19.26		18.75		15.82
mt	7.42					
hm		6.60				
mg				6.03		7.66
il	2.89	6.23		4.26		4.10
per	1.36					
ap	2.69	4.37		1.68		2.02
ce		1.80				2.50

TABLE 4.—*Analyses, norms, and modes of alnoites, monticellite peridotites, and related rocks (continued)*

	MODES					
	1	2	3	4	5	6
Plagioclase						
Nepheline	11	16				
Melilite	30	42	much		3	25
Analcime						
Chrysolite	2		subordinate	19	15	30
Monticellite			subordinate	32	25	10
Aegirite						6
Augite					10	
Biotite	20	18	much	22	30	20
Perofskite	3	4	subordinate	2	7	
Ore	6	7	subordinate			7
Apatite	3	4	subordinate	2	2	
Calcite	3	2				
Melanite		2				
Pectolite	3					
Alteration products	19			21*		
Johannsen	3125			411		

* Green to gray amorphous to submicroscopic alteration products in part from olivine and monticellite, in part from interstitial mineral.

1. Alnoite (turjaite), Haystack Butte, Mont. (FBHB 163). F. A. Gonyer, analyst.
2. Turjaite, Turja, Kola, Russia. J. S. Maclaurin, analyst.
3. Alnoite (melilite-biotite rock), Isle Cadieux, Quebec. H. S. Washington, analyst.
4. Monticellite peridotite, Haystack Butte, Mont. (FBD 163). F. A. Gonyer, analyst.
5. Monticellite alnoite, rich in monticellite. Isle Cadieux, Quebec. H. S. Washington, analyst.
6. Monticellite alnoite, rich in melilite. Isle Cadieux, Quebec. H. S. Washington, analyst.

rectly in the carbon arc and are good to detect quantities down to one or two hundredths of a per cent but will not show thousandths of a per cent. Each specimen gave negative results for all metals.

PETROGENESIS

For the Isle Cadieux alnoites Bowen (1922, p. 32) in a study of the relations of the minerals indicates that the rock originally consisted of augite and chrysolite and was nearly completely consolidated as such. These minerals were then attacked, with lowering temperature, probably by their own interstitial liquid as it changed in composition, and were replaced by monticellite, melilite, and biotite, with marialite, perofskite, and titaniferous magnetite as minor products of the reaction.

"The monticellite is itself replaced by melilite and biotite and the melilite-biotite rock is the end product of the replacement.

"The replacement was accomplished by an alkalic liquid (magma) which formed monticellite from augite by desilicating it and later gave rise to melilite and the more definitely alkalic mineral biotite."

For a nepheline-hauynite alnoite from near Winnett, Montana, Ross (1926, p. 226-227) attributed the following genetic history:

"First, the formation of olivine phenocrysts and a small proportion of nephelite resulted in a porous, partly crystalline rock with a limited proportion of interstitial magma. This residual material contained some water, and other mineralizers, but an additional supply of these elements and of alkalies was added from some deeper source. These combined with the residual magma and reacted with the olivine and nepheline to form the minerals melilite, hauynite, biotite, augite, and iron ores of the second or mineralizer-controlled generation of minerals."

The monticellite peridotite of Haystack Butte is made up largely of monticellite, olivine, and phlogopite. The phlogopite molds about the other minerals, the monticellite is in fairly well-formed grains and shows no signs of resorption, the olivine is bordered by biotite and has been somewhat reacted on. There is nothing to indicate that pyroxene was ever present. The whole rock has the texture and appearance of a typical mica peridotite, and there is nothing to indicate extensive replacement of any of the minerals. It is believed to have crystallized as a nearly closed system so that the solidified rock has nearly the composition of the liquid from which it crystallized. It has been somewhat altered by hydrothermal processes.

The alnoite has about the same SiO_2 content as the monticellite peridotite, and both rocks are high in CaO. On the other hand, the alnoite has very much less MgO than the monticellite rock and much more Al_2O_3, CaO, and alkalies. It is also richer in BaO. Mineralogically, the chief similarity of the two rocks is in the abundance and interstitial position of the phlogopite.

In the alnoite the olivine has been largely replaced by biotite, but otherwise there is no evidence of extensive magmatic or hydrothermal replacement of any of the minerals of the fresh rock.

The alnoite is similar chemically and almost identical in mineral composition to the nepheline-melilite basalts. The latter rocks occur as lava flows and doubtless crystallized from liquids with nearly the compositions of the final rock and have not undergone the extensive replacement advocated by Bowen for the Isle Cadieux alnoite and by Ross for the Winnett alnoite.

The alnoite of Haystack Butte appears to be a normal igneous rock and without evidence of extensive mineral replacement. The unusual character of the rocks is due to the composition of the magmas and not to any later moving solutions.

The analogy of the alnoites and monticellite alnoites to the laboratory system nepheline-diopside is suggestive but is not conclusive. The natural magmas differ considerably from the laboratory melts in that mineralizers, iron, potash, and other constituents are present in the magmas. According to Bowen (1922, p. 11), the temperature of crystallization was

much reduced by these constituents from over 1100° C. in the laboratory melts to below 870° C. in the rocks.

SUMMARY AND GENERAL CONCLUSIONS

In the Highwood area the dike rocks, like the volcanics, form two distinct groups: (1) the older, amphibole phonolite dikes, believed to be related to the quartz latite volcanics; (2) a younger series including pseudoleucite mafic phonolite, augite mafic phonolite, biotite phonolite, syenite, nepheline syenite, and monzonite. The few intrusives of alnoite and peridotite probably belong in the younger series.

It has not been possible to correlate any of the types of dike rock with any particular stock, either on the basis of structural relationships or of petrography. Apparently the dike magmas came from a greater depth than the present position of the erosion surface. A close relationship may exist between the dikes and the stocks at great depth, but such relationship is not evidenced at the surface. The dikes were intruded after the rock of the stocks had crystallized.

Detailed studies of a number of intersecting dikes indicate that the dikes were intruded into fractures which developed outward from the central part of the area. Locally the development of fractures was impeded by the presence of laccolith, and "shadow areas" containing few dikes are recognizable to the east of Square Butte and Round Butte laccoliths—*i. e.*, on the side of these laccoliths away from the mountains.

The chemical variation in the younger series of dikes is attributed principally to magmatic differentiation at depth. The original magma for this series is believed to have had about the composition of the augite and pseudoleucite mafic phonolites. The late-stage differentiate gave rise to the syenite dikes which are the youngest and most salic of the series. These dikes are comparable to the syenite of the stocks. The undifferentiated magma gave rise to augite and pseudoleucite mafic phonolites and to biotite phonolite. The pseudoleucite was derived from analcime or leucite. The difference between the pseudoleucite mafic phonolite and the augite mafic phonolite is essentially one of texture; the transition from the former to the latter was accomplished by the disintegration of the pseudoleucite units and the coarsening of the feldspar derived from them. Where conditions were favorable, as in the headed dike, gravitative separation occurred before the pseudoleucite disintegrated. In the headed dike this lighter differentiate, containing 50 per cent of pseudoleucite, crystallized before the pseudoleucite could be reworked to form a coarse-grained syenite.

The biotite phonolite forms only dikes or small irregular intrusives. Petrographically it is unlike the rock of any of the stocks or laccoliths

or of the extrusives. Although only one chemical analysis of the biotite phonolite is available, and its mineral composition varies considerably, the average chemical composition probably is not greatly different from that of the augite and pseudoleucite mafic phonolites. Instead of producing pseudoleucite, augite, and olivine, its magma crystallized principally as sanidine, nepheline, and biotite. The reason for the crystallization of different minerals in the two types of rock is unknown.

The considerable range in the percentage of felsic minerals in the biotite phonolite rocks is due at least in part to the assimilation of granitic material presumably derived from the basement which underlies the several thousand feet of sedimentary strata and volcanics. The amount of metamorphism of the country rock associated with the biotite phonolite dikes is small, and this is what would be expected after the magma had been rendered impotent by reaction with numerous inclusions.

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IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA

PART IV. The Stocks

BY C. H. BURGESS

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ABSTRACT OF PART IV

The largest of the stocks of the Highwood Mountains is about 3 miles long. Most of the stocks are made up of shonkinite and mafic syenite. The stock of East Peak is a mafic pseudoleucite-augite syenite. Small bodies of leucite-rich rocks—missourite and niligongite—are present in the Shonkin stock. Leucite malignite

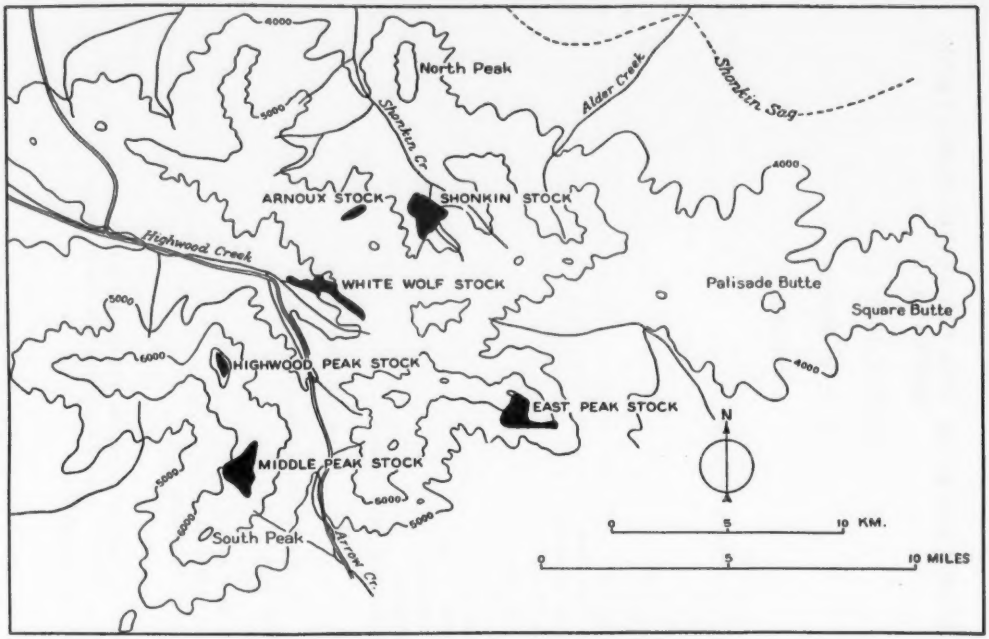

FIGURE 1.—*Index map of the Highwood Mountains*
Showing the location and size of the stocks (black).

makes several small bodies. In the stocks, augite is the predominant mineral, sanidine is the chief felsic mineral, altered nepheline, olivine, and biotite are in moderate amounts, and plagioclase, hornblende, and leucite are rare. The early magmatic sanidine is high in barium.

The Highwood Peak stock is made up chiefly of felsic syenite and monzonite.

DISTRIBUTION AND GENERAL CHARACTER

Six stocks have been mapped in the Highwood Mountains. Their distribution is shown by Larsen (1941, Pl. 1) and in Figure 1. A number of smaller irregular crosscutting bodies have also been studied, and more are no doubt present but, owing to their similarity to the volcanic rocks and to poor exposures, they have not been mapped.

The stocks are individually small and irregular in outline. They intruded the Cretaceous sedimentary rocks and the mafic phonolites. The stocks are surrounded by broad irregular zones of hydrothermal contact metamorphism, indicating that abundant mineralizers accompanied the intrusives.

The Highwood Peak stock consists of monzonite and later felsic syenite. The other stocks are composed principally of shonkinite and mafic syenite. These rocks are generally variable in the ratio of dark minerals to light and in size of grain, although the mafic pseudoleucite-augite syenite of East Peak is approximately homogeneous in both these respects. These variations are accomplished by progressive change in rock of a single age and by abrupt changes at sharp contacts between rocks whose difference in age is probably very slight. The serial variations are subtle and difficult to recognize.

Augite is the predominant dark mineral; biotite and olivine also occur; hornblende is absent. Sanidine is the chief light mineral and with turbid material commonly forms round patches of pseudoleucite. Leucite is rare.

SHONKIN STOCK

The body of granular igneous rock on both sides of the middle fork of Shonkin Creek outcrops over an essentially triangular area approximately a mile on a side. (*See* Figure 2.) Exposures are fair.

The rock though dominantly shonkinite varies considerably in the relative amounts of light and dark minerals as well as in texture and in grain size. An unsuccessful attempt was made in the field to discover a systematic distribution of the different kinds of rock. In the laboratory the collection was separated into 14 groups which were established on the basis of similarity of size of grain and of relative amounts of light and dark minerals as estimated by inspection. Several dozen specimens failed to fit into any of the groups. No systematic correspondence of grain size

or content of dark minerals of the rocks in any of the groups with their position in the stock was detected. Locally the different types are separated by sharp boundaries. Small bodies of breccia are present in which the matrix and fragments have closely similar compositions. The matrix

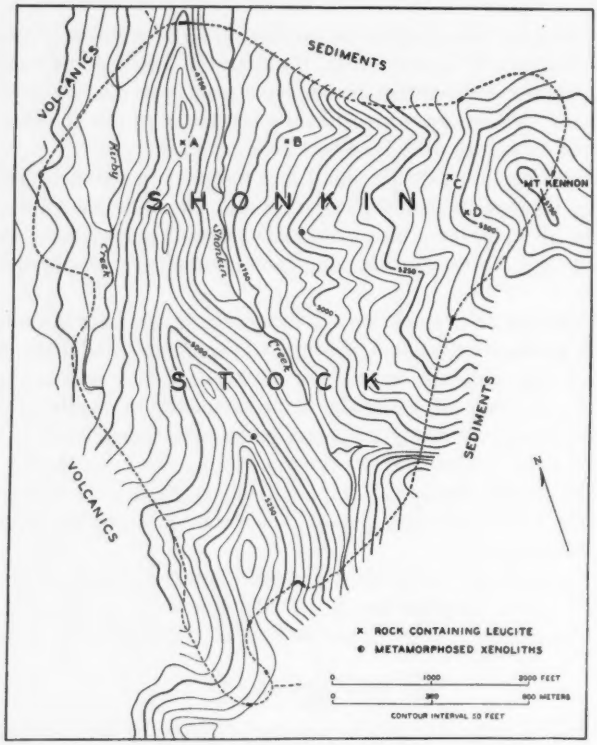

FIGURE 2.—*Shonkin stock*

of every breccia observed is finer in grain than the fragments. In other cases the variation is apparently transitional.

With decrease in the content of dark minerals, the shonkinite type grades to mafic nepheline syenite. Augite and sanidine (barium sanidine is also present) are the only essential constituents present in all specimens. The augite ranges from tiny crystals barely recognizable under the microscope to phenocrysts 1.5 cm. long. Sanidine reaches a maximum dimension of 2 mm. Olivine and biotite are essential minerals in most,

but not all, of the rocks. Anhedra of olivine attain a maximum diameter of 2 mm. but average .3 to 0.5 mm. Foils of biotite 7 mm. long were observed, but this mineral is generally in much smaller grains. Pseudoleucite is prominent in much of the rock and is made up of sanidine and fine undetermined material which may be an alteration product of nepheline (Pl. 1).

Poorly preserved pseudoleucite was seen (Pl. 2, fig. 1) in a specimen from the Shonkin stock. A specimen of rock with unusually well preserved pseudoleucite was collected from float in Shonkin Creek, west of Mt. Kennon. It has phenocrysts of pseudoleucite and unzoned pyroxene in a matrix composed of crystals of sanidine, shreds of biotite, and fibrous natrolite; it might be called mafic fergusite or pseudoleucite shonkinite. Leucite is very rare in the rocks of the Shonkin stock and was found only as sparse grains in two thin sections. Iron ore and apatite are constant accessories. Zircon and sphene are absent. The texture is equigranular to porphyritic.

The heavy minerals separated from several of the rocks by bromoform (Sp. G. 2.89) made up from 45 to 89 per cent of the rocks.

TABLE 1.—*Chemical analyses, norms, and modes of stocks of the Highwood Mountains*

	Analyses							
	1	2	3	4	5	6	7	8
SiO_2	46.06	46.62	48.18	49.59	51.00	51.75	52.05	65.54
TiO_2	.73	.76	.55	.36	.13	.23	.47	.11
Al_2O_3	10.01	12.48	11.28	14.51	17.21	14.52	15.02	17.81
Fe_2O_3	3.17	4.78	3.29	3.51	2.41	5.08	2.65	.74
FeO	5.61	4.44	3.84	5.53	4.23	3.58	5.52	1.15
MnO	tr	.09	.05	tr	tr	tr	tr	tr
MgO	14.74	8.90	12.89	6.17	6.19	4.55	5.39	.98
CaO	10.55	11.94	9.22	9.04	9.15	7.04	8.14	1.92
Na_2O	1.31	1.97	1.94	3.52	2.88	2.93	3.17	5.55
K_2O	5.14	4.42	6.57	5.60	4.93	7.61	6.10	5.58
H_2O-	1.44							
H_2O+		2.83	1.55	1.95	.63	2.25	.35	.54
CO_2			none				none	tr
P_2O_5	.21	.18	.53	.15	.33	.18	.21	tr
SO_3	.05			.02	.03	tr	.02	
S		.05	.03					
BaO	.32	.60	.20	.49	.34	.30	.42	
SrO	.20	.04		.21	.14	.07	.28	
Cl	.03			.13	tr	.05	.24	
Cr_2O_3			.05				none	
Li_2O						tr		
	99.57	100.10	100.17	100.78	99.60	100.14	100.03	99.92
Cl=O	.01			.03			.06	
	99.56			100.75			99.97	
Sp.G.	2.98	2.84	2.84	2.83	2.91	2.62	2.87	2.54

TABLE 1.—*Chemical analyses, norms, and modes of stocks of the Highwood Mountains (continued)*

	1	2	3	4	5	6	7	8
NORMS								
Q								6.18
or	0.56	13 34	13.90	33.36	29.47	45.04	36.14	32.80
ab				.52	12.05	3.67	6.81	47.16
an	6.12	12.23	2.78	7.23	19.18	3.89	8.62	7.23
ne	5.96	9.09	8.80	15.62	6.82	11.36	10.79	
lc	23.54	10.03	19.62					
di	35.71	38.83	31.64	29.32	18.48	23.86	24.97	1.79
hy								2.96
ol	18.50	4.90	18.46	5.58	5.24	1.25	6.09	
mt	4.64	6.96	4.87	5.10	6.03	8.12	3.94	1.16
hm								
il	1.37	1.52	1.06	.76	.30	.46	.91	
ap	.34	.34	1.24	.34	.67	.34	.34	
Position	(III)IV. 1(2).2″. 2.″2	III.″7. 2(3). (2)3″.	III.(7) 8.1″.2	III.6. ″2.3	II.5(6) 3.3	II(III). ″6.1(2). 2(3)	II(III). ″6.2.3	I.″5. (1)2. 3(4)
MODES (VOLUME)								
Quartz								
Sanidine		10					60	
Plagioclase				64				
Nepheline								
Leucite	16	40	54					
Analcime	4							
Zeolites	4							
Biotite	5		1	1				
Amphibole							4	
Pyroxene	50	40	34	23			29	
Olivine	15	7	10	8			1	
Iron Ore	5	3	1	4			5	
Apatite							1	
Muscovite								
Johannsen	3125	3121	2125	2117	2214	2117	2113	219

1. Missourite, Shonkin Stock. Analyses by E. B. Hurlburt. Described by Weed and Pirsson (1896, p. 315-323). The mode was calculated by Pirsson.

2. Leucite-rich shonkinite. Leucite fasinite (F.B.Sh.S. 247) from southern end of North Peak. F. A. Gonyer, analyst. Rosiwal on thin section of 370 mm². Heavy liquid separation gave 34% leucite + analcime by weight.

3. Leucite ijolite. (Fergusite of Johannsen) (F.B.Sh.S. 14). Shonkin Stock. Crest of ridge between Shonkin and Kirby creeks, at location A of Figure 2. Rosiwal on thin section of 400 mm². F. A. Gonyer, analyst. Heavy liquid separation gave 42% leucite + analcime by weight.

4. Mafic pseudoleucite syenite from East Peak stock. Also described by Pirsson (1905, p. 105). Mode estimate.

5. Monzonite from Highwood Peak stock. Also described by Pirsson (1905, p. 76-83). Mode estimate. E. B. Hurlburt, analyst.

6. Fergusite from Arnoux stock. Also described by Pirsson (1905, p. 83). E. B. Hurlburt, analyst.

7. Mafic syenite from Middle Peak stock. Also described by Pirsson (1905, p. 83). Rosiwal by Pirsson.

8. Syenite from Highwood Peak stock. Also described by L. V. Pirsson (1905, p. 60). L. V. Pirsson and W. L. Mitchell, analysts.

The type specimen of leucite-rich rock, missourite, was collected by Weed (Weed and Pirsson, 1896) from float. The locality designated "D" on the map of the Shonkin stock (Fig. 2) is the only place where missourite was found in this work, and Weed's specimen probably came from

FIGURE 1. AUGITE, ORE, LITTLE BIOTITE, AND PSEUDOLEUCITE
Form of the original leucite is lost.

FIGURE 2. COARSE ROUNDED PSEUDOLEUCITE IN SHONKINITE

PHOTOMICROGRPHS OF SHONKINITE FROM SHONKIN STOCK
Showing coarse pseudoleucite.
White is orthoclase, gray is cloudy isotropic. x 33. Ordinary light.

FIGURE 1. SHONKINITE FROM SHONKIN STOCK
Phenocrysts of pseudoleucite, augite, and olivine in groundmass of biotite and pseudoleucite.

FIGURE 2. COARSE SHONKINITE FROM ARNOUX STOCK
Contains pyroxene, biotite, orthoclase, cloudy isotropic material, and a little fresh leucite and olivine.

FIGURE 3. BRECCIA OF MAFIC NEPHELINE SYENITE
Cut by dikelet of nepheline syenite. Arnoux stock.

FIGURE 4. FERGUSITE (type specimen), ARNOUX STOCK
Contains pseudoleucite in matrix of augite, biotite, and sanidine.

HAND SPECIMENS OF ROCKS FROM SHONKIN AND ARNOUX STOCKS

here. Several ledges rise a few feet above the grassy slopes over an area a few hundred feet across. No external contacts of this body of rock were visible. The rock is transected by numerous dikes, the narrowest a fraction of an inch wide, and the largest 6 inches. The missourite is a coarse granular dark rock with conspicuous anhedral black augite. A few flakes of biotite are 1 cm. across, but grains average about 5 mm. Brown olivine occurs as 2- to 3-mm. grains. The only light-colored constituent is leucite, which on a fresh fracture is distinctly green. The microscope reveals that the augite is strongly zoned. The olivine is anhedral, fresh, and rich in inclusions of ore; most grains are mantled by biotite. The leucite is clear and shows the characteristic twinning. It contains chadacrysts of olivine and augite and rare spongy grains of sanidine (?). Biotite is clearly interstitial to the other minerals and mantles the augite, olivine, and leucite indiscriminately. Sinuous films of the biotite separate grains of each of these minerals. Apatite is accessory. An analysis of this rock is shown in column 1 of Table 1.

The minerals in the rock of the dikes which cut the missourites are the same as those of the missourite, but in different and varying proportions. In all of them leucite is by far the most important constituent, occupying not less than half the volume of the rock and usually three-fourths or more. In some of the dikes several inches wide the dark minerals are concentrated in scattered patches. Leucite is the dominant mineral, even in these patches. Under the microscope brown kaolinlike material appears to be common in the rock of the dikes. Chadacrysts of biotite are abundant in the augite.

The missourite is crossed by fractures whose walls show hydrothermal attack in which secondary pyroxene has been introduced.

The leucitic rock from the locality designated "A" on the map (Fig. 2) is made up of approximately equal amounts of leucite and dark minerals and corresponds to niligongite (Tröger, 1935, p. 258, 259). A chemical analysis, norm, and mode of a typical specimen are given in column 3 of Table 1. The rock forms small ledges on top of the ridge. No external contacts are visible. In this rock, augite crystals attain lengths of several millimeters, and round grains of olivine average about 1 mm. in diameter. A small quantity of biotite is present. Small grains of ore are accessory, as well as tiny needles of apatite in the felsic minerals.

ARNOUX STOCK

A small body of granular rock exposed along a tributary of Shonkin Creek was named the Arnoux stock by Pirsson. He did not study this stock in the field but based his descriptions on specimens collected by Weed.

Numerous crags and ledges provide good exposures, and near the eastern end of the stock Chimney Rock forms a striking eminence. The age relations of the intrusive to the volcanic rock is not clear. The sedimentary rocks have been metamorphosed to dense and brittle quartzites. (*See* Figure 3.)

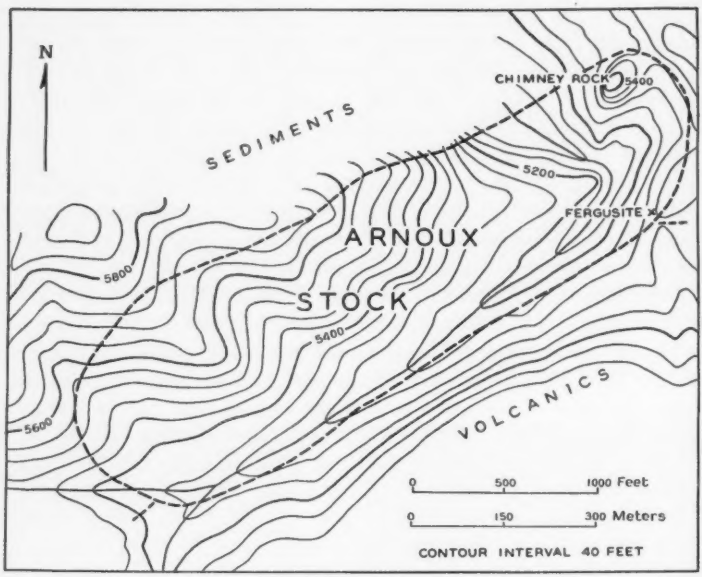

FIGURE 3.—*Arnoux stock*

Shonkinite and mafic syenite are the main types of rock in this stock. Variation in the relative amounts of light and dark minerals is not so extreme as in the Shonkin stock, probably not exceeding a range of 35 per cent to 50 per cent of augite. This variation was found between different outcrops, and not in the rock at one outcrop or in one hand specimen. The shonkinite and mafic nepheline syenite are cut by small dikes of felsic nepheline syenite (Pl. 2, fig. 3).

In a specimen of coarse shonkinite from Arnoux stock (Pl. 2, fig. 2) the crystals of augite are euhedral to subhedral. They enclose poikilitically olivine, ore, and apatite. Grains of olivine are commonly altered to green biotite and ore about the margins and along cracks. Biotite molds about the augite and olivine. Sanidine and the common cloudy undetermined material which may be an alteration product of nepheline

are the principal light minerals. The cloudy material forms inclusions in the grains of sanidine or forms separate grains among the other minerals. Leucite forms large grains which show the characteristic twinning. Small wisplike stringers of sanidine (?) penetrate the leucite. Rarely patches which in section appear as a network of anastomosing veinlets of sanidine (?) are found in leucite.

The mode of this rock as determined from an inspection of the hand specimen and thin section is approximately:

	Volume (per cent)
Sanidine and cloudy material	45
Augite	40
Biotite	8
Ore and apatite	4
Leucite	2
Olivine	1

Specimen 2¼ inches long

One new point of minor interest is the presence of gneissic shonkinite in this stock. The usual minerals are present, but they have suffered granulation and have been drawn out into striplike aggregates. At one place in the stock breccia is exposed. The matrix is an almost aphanitic rock, with sparse phenocrysts of pseudoleucite and augite. In the fragments the pseudoleucite and crystals of augite are larger than in the matrix of the breccia. The fragments are round to subangular, and many are rimmed by a thin mantle of syenite. Under the microscope the rocks of the matrix and fragments are so similar that they can be distinguished only by differences in their phenocrysts (Pl. 2, fig. 3).

The Arnoux stock is the type locality of fergusite, a rock which consists mainly of pseudoleucite in a matrix of augite, biotite, sanidine, ore, and apatite. Sanidine and nepheline or natrolite are the ingredients of the pseudoleucite (Pl. 2, fig. 4). A chemical analysis and norm of this rock appear in column 6 of Table 1. This rock forms one large outcrop at the eastern end of the stock.

WHITE WOLF STOCK

In the field season of 1933, an elongate stock not described by Pirsson was found within the drainage of the north fork of Highwood Creek, one of whose tributaries is White Wolf Creek from which the stock has been named (Fig. 4). In 1934 this stock was studied in the field, using an enlargement of the forest map as a base, and locating points on it by topography and pacing. The errors are probably large. Exposures are poor (Pl. 3, fig. 1). Although outcrops on the tree-covered northern slopes are rare, low ledges projecting through the turf and soil on the

southern slopes offer somewhat better opportunities for study. The contact of the stock with the country rock was not seen.

Petrographically the White Wolf stock is very much like the Shonkin stock. The same range of variation in size of grain, texture, and ratio of

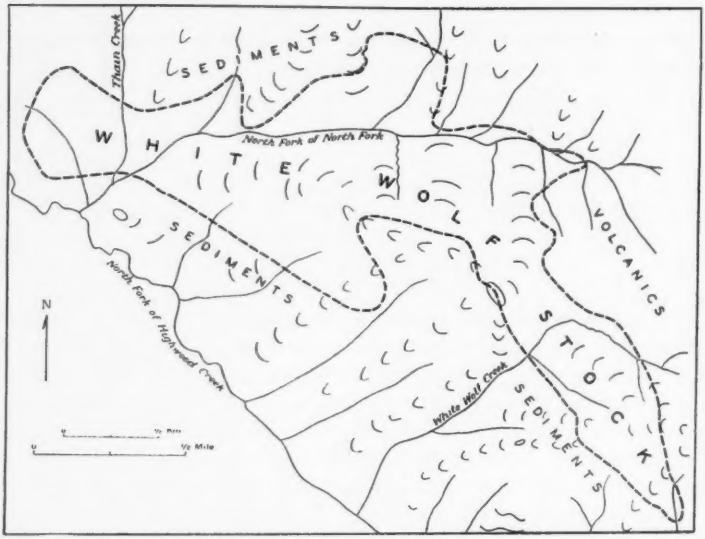

FIGURE 4.—*White Wolf stock*

light minerals to dark is found in the shonkinite and mafic nepheline syenite, which are the dominant types. As in the Shonkin stock, these rocks are cut by narrow dikes of leucocratic syenite and they form breccias in which the matrix differs from the fragments principally in being finer-grained. No systematic distribution of the different varieties of rock was found.

Strongly mafic rock like that of the Middle Peak stock is found as rare isolated masses a few feet across, cut by narrow dikes of nepheline syenite, and as inclusions in shonkinite. It consists principally of biotite and augite.

EAST PEAK STOCK

A preliminary examination of the East Peak stock showed that it is homogeneous, and only one day was spent on the stock. No large-scale map was made of the stock, but its general size and shape are shown in Figure 1. (*See also* Larsen, 1941, Pl. 1.)

East Peak is a high point on the ridge of volcanic rocks extending eastward from Arrow Peak. From the crest of East Peak the granular rock of the stock extends southward to the gentle slopes at the head of Davis Creek. It forms very steep slopes, characterized by cliffs and crags which rise above the talus. Earlier observations by Hurlbut suggest that the stock has been intruded into the volcanic rocks.

The rock of this stock was called leucite shonkinite by Pirsson, but the content of dark minerals is too low for shonkinite, and the name mafic pseudoleucite-augite syenite seems more appropriate.

The chemical analyses, norm, and mode of this rock are given in Table 1, column 4. Augite averages nearly 1 mm. in length. Olivine averages .5 mm. in diameter; a few large grains reach 5 mm. This mineral is commonly mantled by very thin films of biotite and is crossed by sparse cracks filled with serpentine. Biotite is a minor constituent of this rock. Two kinds of feldspar are present: one is barium sanidine, which occurs in irregular grains about .3 mm. across; the other is finer in grain and is one of the ingredients of the pseudoleucite. It is probably normal sanidine. The other important mineral in the pseudoleucite is analcime, in irregular films and grains. Leucite is present in some sections and has been replaced along cracks by films of analcime. Pirsson separated the white minerals from the rock with heavy liquids and had those with a specific gravity of 2.38 analyzed chemically. The results showed the presence of equal amounts, by weight, of analcime and leucite. In one section of the rock a brown substance, which shows the wedge pattern characteristic of twinning in leucite, forms irregular grains which seem to have escaped the conversion to pseudoleucite. This brown substance has the index of refraction of analcime.

MIDDLE PEAK STOCK

Middle Peak is a high point on the ridge running south from Highwood Peak. Its western slope descends to the bottom of a canyon whose walls are covered by evergreen timber. In this timber, exposures of bedrock are sparse, but in the bottom of the canyon, and on the ridges at the top of the canyon walls, outcrops are to be found, usually as low ledges, although some are bold cliffy masses as much as 15 feet high.

Because of the paucity of outcrops, it is possible in only a few places to be certain within a few feet of the position of the contact between the stock and country rock.

The Middle Peak stock as mapped during the present work is 1½ miles long and has a maximum width of nearly a mile (Fig. 5). Pirsson

describes it as a body of "basic syenite" about 2 miles across, with an apophysis of rock somewhat richer in biotite extending another 2 miles to the south. This apophysis was not discovered during the writer's field work, although an effort was made to trace it out from the southern end

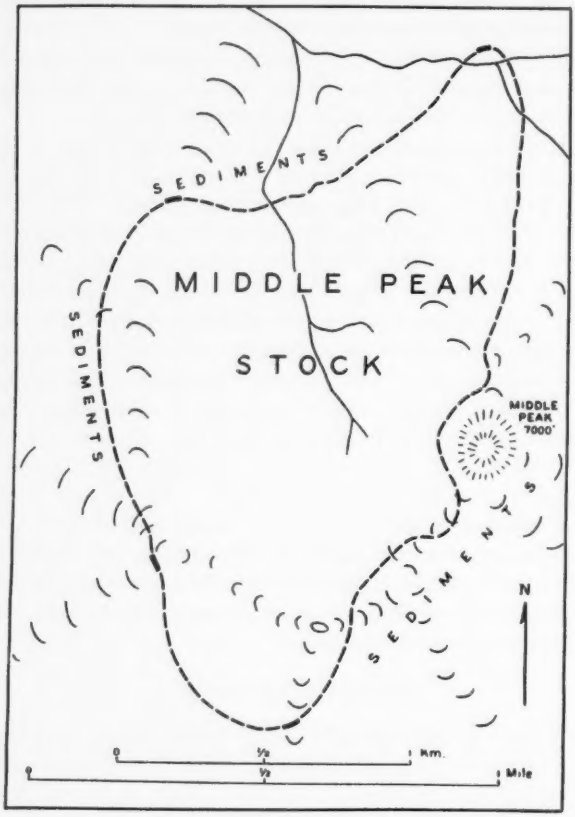

FIGURE 5.—*Middle Peak stock*

of the stock. Granular rock, in masses not more than 100 feet across, insofar as can be estimated from their float, occurs on the ridge south of the stock. It is possible that Pirsson saw several of these and assumed they were one body.

The present work has revealed more variation in the stock rock than Pirsson (1905, p. 23) seems to have recognized. He states, "The rock

composing this intrusion varies somewhat in fineness of grain and relative amount of feldspathic and ferromagnesian minerals, but in general is of medium nature." The present writer found that the rocks range from felsic nepheline syenite to biotite pyroxenite. Shonkinite and mafic nepheline syenite are the dominant types, and, although there is no clear factual evidence to confirm it, shonkinite seems to predominate. No correlation of the types of rock with their position in the stock has been possible.

Varieties of syenite similar to the gray syenite of Highwood Peak are found in massive ledges several feet across in the Middle Peak stock and in dikes up to a few inches wide that cut the shonkinite and ultramafic types. A noticeable feature of the massive syenite is the presence of inclusions, the largest of which is 4 inches across; they are habitually angular and dark and consist almost exclusively of biotite and augite.

Brown garnet forms skeletonlike grains in interstices among the feldspar crystals of the syenite. The syenite of the narrow dikes is finer in grain than the massive variety and contains interstitial zeolitic material, usually fibrous, which may have been derived from nepheline. This material makes up as much as 20 per cent of the rock. One of the dikes consists of monzonite in which microperthite encloses chadacrysts of biotite and augite. Natrolite and analcime occupy interstices among the feldspars.

Mafic nepheline syenite (basic syenite of Pirsson) forms massive ledges along the ridge at the eastern edge of the stock and near the bottom of the canyon. In an outcrop about 50 feet from the contact with the metamorphosed sediments the rock is indistinguishable from the same type in the center of the stock. The mafic syenite is an equigranular gray rock containing pyroxene crystals 3 to 4 mm. long. The augite forms subhedral grains and contains inclusions of ore, apatite, and biotite. Crystals of olivine reach a maximum dimension of 1 mm.; they contain many undetermined inclusions and are habitually enveloped in a shell of ore, which in turn is encased in biotite. The width of the shell of ore varies from grain to grain; in some cases the original material has been completely replaced by ore. Ore-filled cracks traverse some of the grains of olivine. Most of the biotite in the rock is found as mantles around grains of ore or as incomplete sheaths about olivine and augite, but grains of this mineral do occur independently; several large crystals contain a great abundance of ore. The principal feldspathic constituent of the rock is barium sanidine. This mineral forms large anhedra as much as 1 mm. across and many smaller interstitial grains. Sparse grains of cloudy material may be nepheline, though positive tests were not obtained. Analcime makes up a few per cent

of the rock, forming angular grains in interstices among the feldspar crystals and penetrating some of them as fine wiggly films. None of the colorless diopside mentioned by Pirsson was seen. The analysis, norm, and mode of this rock appear in column 7 of Table 1.

Some of the shonkinitic types are coarser, and some finer than the mafic syenite, but the minerals are the same and have the same habits. A few features deserve special attention. One is the occurrence of aggregates of fine pyroxene and ore, which are surrounded by biotite. Turbid material, which high magnification reveals to be bundles of fibers, produces mottled patterns in the feldspar of some of the shonkinitic types and may be a product of alteration of nepheline. Small amounts of zeolitic material are seen. In rare specimens the occurrence of the feldspar, the fibrous material, and fine analcime in round areas suggests that these areas may be pseudoleucite. The shonkinite contains, at some localities, bodies of more mafic rock which are tabular in shape and several inches wide or are irregular pods as much as 3 feet across. Some of these bodies are separated from the country rock by sharp contacts; others blend into it through a zone an inch, or several inches, wide. The nature of the contact appears to be independent of the shape of the body.

Soft and crumbly, highly mafic rock is an interesting minor constituent in the Middle Peak stock. The only proved relation to other rocks is that it is penetrated by felsic syenite in dikes varying in thickness from 2 inches down to mere films.

According to Pirsson, the contact phase of the mafic syenite contains thin tablets of feldspar "oriented parallel to the contact in a rude flow structure." These tablets of sanidine average 3 to 4 mm. in length and are twinned according to the Carlsbad law. The dark minerals are pyroxene, in green grains .5 mm. long, biotite, green hornblende, and ore. They occur among the feldspar plates. This type of rock varies considerably from place to place in the habit of the minerals and their relative amounts. Since it occurs independently of the contact, it seems that this cannot be a chill phase. The same sort of rock is found elsewhere in the Highwood Mountains as dikes cutting sediments, and it is likely that the Middle Peak occurrences are similar bodies.

HIGHWOOD PEAK STOCK

GENERAL DESCRIPTION

The highest peak in the mountains is mantled by a felsenmeer through which a few outcrops of bedrock project (Pl. 3, fig. 2). This mantle extends far down the slopes before it is divided into tonguelike strips of talus separated by tree-covered slopes. Granular rock appears in

FIGURE 1. HIGHWOOD PEAK
Looking westward from North Fork of Highwood Creek. White Wolf stock in foreground.

FIGURE 2. FELSENMEER ON EASTERN SIDE OF HIGHWOOD PEAK

VIEWS OF HIGHWOOD PEAK

the outcrops near the top of the mountain (Fig. 6). The contacts are not mapped very accurately as outcrops are poor, and in only the few places where the boundary is shown by a heavy line could the contact be located to within 200 feet.

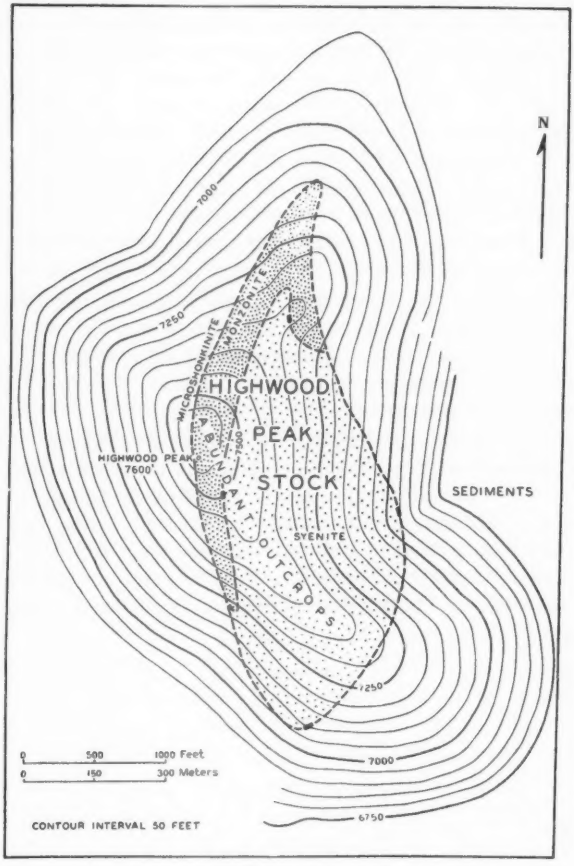

FIGURE 6.—*Highwood Peak stock*

The rocks of the Highwood Peak composite stock include syenite, pegmatite, monzonite, and microshonkinite and will be described in sequence. Exposures are so poor that details of distribution of these rocks and of their mutual relationships cannot be determined.

WHITE SYENITE

Syenite is probably the most voluminous type of rock in the stock. Certainly it predominates over the monzonite and pegmatite in the outcrops now accessible.

The white syenite is seen in abundant outcrops on the ridge southeast of the peak and to the northeast of the peak as well. It weathers into slabs, the largest of which are a couple of feet thick and 6 or 8 feet across. These slabs constitute the felsenmeer on the eastern side of the peak. The white syenite is coarse in grain. Barium orthoclase, by far the most abundant ingredient, forms plates as much as 1 cm. long and 2 mm. thick, which are imbedded in finer feldspar. Small cavities among the feldspar render the rock somewhat porous. Thin sections show that the feldspar is zoned. Albite is present in separate grains and in microperthitic intergrowths with the barium orthoclase. In the same thin section albite occurs as a core in one grain of barium orthoclase and as a rim about another grain. The microperthitic intergrowth is found throughout some crystals of barium orthoclase; in others it is limited to a rim. The albite in some specimens is in excess over the orthoclase, forming antiperthite. Accessory quartz fills angular interstices between the feldspar grains. Rare grains of carbonate have a similar occurrence. Sericite accompanies the carbonate or forms irregular patches in the feldspar. Augite, the principal ferromagnesian mineral, constitutes only a small percentage of the rock, and biotite even less. In some thin sections the mafic minerals occur as aggregates 2 mm. across. Some of the augite has been altered to fibrous hornblende. The rock is free from olivine. Sphene, apatite, and ore are constant accessories. An analysis and norm are shown in column 8 of Table 1.

GRAY SYENITE

The gray syenite of the Highwood Peak stock is abundant on the southern side of the spur which runs southwest from the top of the peak. This rock differs from the white variety in the following particulars. The gray rock is more compact, it is generally finer in grain, the feldspars are more nearly equidimensional, it is not so rich in microperthite, it lacks quartz, except for a few grains in one thin section, it is generally richer in dark minerals, it contains rare chains of sphene grains, and it encloses xenoliths varying from angular to round and from shonkinitic to highly mafic. Microscopic study shows that one specimen thought to be gray syenite is monzonite.

PEGMATITE

Near the southern end of the stock, the gray rock is cut by pegmatite. In one specimen the pegmatite consists of quartz and orthoclase and

appears to be a local facies of the white syenite. Blocks of white syenite cut by pegmatite dikes as much as 8 inches wide are found in the felsenmeer on the eastern side of the mountain. The grain size of the feldspar increases toward the center of the dikes, where some of the plates reach a breadth of 4 cm. Brilliant crystals of aegirite project into miarolitic cavities among the feldspars. The feldspar is microperthite. Sphene and muscovite are accessory minerals.

MONZONITE

A dark-gray granular rock, which weathers to massive blocks a foot or more across, is found in the outcrops above the syenite on Highwood Peak. This monzonite (2214P of Johannsen) is apparently less abundant than the syenite. It is transected by syenite dikes several inches wide. No pegmatites were found cutting the monzonite, and no evidence clearly dating it with respect to the microshonkinite was recognized.

The texture of the rock is hypidiomorphic granular. Pyroxene crystals 3 to 4 mm. long appear in thin section as the usual faintly green subhedral augite, with inclusions of ore and biotite. No olivine is present. Biotite is a prominent constituent of the rock, in irregular grains about 1 mm. across. It surrounds aggregates of ore and fine pyroxene in which the minerals are intermixed, not zonally arranged. Green hornblende is abundant in one thin section and in some places has been clearly formed at the expense of the augite.

Barium orthoclase is the most abundant mineral in the rock. As formless grains about 1 mm. across it encloses poikilitically all the other minerals. Zoned plagioclase ranges in composition from medium andesine to sodic labradorite and forms individuals .5 mm. across. It shows albite twinning. From the gelatinous silica tests Pirsson suspected the presence of nepheline in this rock. Although attempts to identify this mineral positively by the immersion method have failed, some turbit material in the thin sections probably is nepheline. Sodalite is an accessory mineral. An analysis and norm of the monzonite are shown in column 5 of Table 1.

MICROSHONKINITE

Microshonkinite, called micromonzonite by Pirsson, is a dark and dense rock which is found north and northwest of the top of Highwood Peak. It was considered by Pirsson to be a border facies of the monzonite. Although it is different from the volcanic rocks farther down the western slope of the mountain, it was mapped as volcanic rock. In no place was it seen in contact with the volcanic rocks or monzonite, nor was any gradation evident between it and the granular monzonite. It is cut by narrow dikes of syenite.

Augite phenocrysts as much as 1 cm. long are embedded in a dark gray aphanitic groundmass which is composed of feldspar, pyroxene, and shreds of biotite, having an average grain size of about .02 mm. The index of refraction of the feldspar is lower than that of the balsam; no twinning was seen. It appears likely, therefore, that this rock contains no plagioclase. A striking microscopic feature is the presence of aggregates of fine pyroxene surrounded by biotite. In some cases kernels of ore occur in the pyroxene.

AGE RELATIONS

Not all the age relations of the rocks on Highwood Peak can be determined on the basis of field evidence. The pegmatite and probably the white syenite are younger than the gray syenite, and the white syenite is younger than the monzonite and microshonkinite, but the relations of the monzonite and microshonkinite to each other are not known. Neither is the age relation between the volcanic rocks and the monzonite or the microshonkinite known.

MINOR INTRUSIVES

In addition to the major stocks, small bodies of granular rock are found at various localities in the Highwood Mountains. They will be described individually.

(1) Shonkinite of coarse grain is found in a shallow saddle in the ridge running northward from Highwood Peak. So far as could be judged from the poor exposures, the greater horizontal dimension of this intrusive does not exceed a few hundred feet. Loose blocks of more mafic, fine-grained shonkinite occur at this locality also. The country rock about this intrusive is sedimentary.

(2) In the bottom of the third saddle south of Middle Peak, in the ridge leading to South Peak, loose blocks of shonkinitic types are strewn over the ground. The country rock here is sedimentary. No features were observed in the field which indicated the lateral extent of this intrusive rock, but it is probably to be measured in hundreds of feet or yards. Although some pieces of this rock are as coarse as that in the small intrusive north of Highwood Peak, others are medium-granular.

(3) An intrusive is exposed near the head of a southward-flowing tributary of the North Fork of the North Fork of Highwood Creek, about the NE. corner of sec. 22, T. 20 N., R. 9 E. It is probably less than a quarter of a mile across. Although the rock at this locality has the usual shonkinitic composition, several features deserve mention. One is the development of gneissic structure by localization of the dark minerals in irregular streaks which attain widths of several millimeters and which alternate

with similar streaks of the white minerals. These bands vary in attitude from plane to twisted and gnarled. The gneissic rock is cut by many dikes a few inches wide, or less, of a dense gray rock with phenocrysts of augite and pseudoleucite set in an aphanitic groundmass. A second interesting feature of this intrusive is the presence of breccia. Not all the rock at this locality has gneissic or breccia structure. No intelligible relation between the different types was discovered.

(4) A small intrusive surrounded by sedimentary rocks was discovered about a quarter of a mile east of the eastern end of the Arnoux stock. The rock is the common sort of shonkinite and of no special interest.

(5) Two small masses of granular rock outcrop on the northern slopes of East Peak. They form bold cliffy pinnacles and are surrounded by volcanic rocks. The rock is indistinguishable from that of the East Peak stock, from which these small intrusives may be satellitic.

(6) At and near the top of Thain Mountain several types of granular rock are found in the midst of volcanic rocks. The relative age of the coarse rock and of the extrusives and the lateral extent of the coarse rock are not known, although the latter probably does not exceed a quarter of a mile.

The most conspicuous rock at Thain Mountain is a syenite porphyry in which the phenocrysts of tabular feldspar attain lengths of 2 cm. and thicknesses of 6 mm. They lie in a groundmass of finer feldspar and mafic minerals. In thin section this rock resembles the white syenite of the Highwood Peak stock. The large phenocrysts are zoned barium sanidine. Microperthite is not abundant in this rock; it was found in some of the feldspar of the matrix and as a narrow irregular fringe at the margin of one of the large phenocrysts. The finer feldspar is probably normal sanidine. The principal mafic constituent of the rock is augite in grains which average 1 mm. in length. Hornblende forms discrete grains and is associated with the pyroxene as uralite. Ore and sphene are accessory. Quartz is absent. The dark minerals occupy only a small percentage of the volume of this rock.

At one small exposure felsic syenite cuts mafic syenite. The mafic syenite contains inclusions of a biotite-pyroxene rock.

(7) The irregular intrusive in the dark volcanic rocks west of Kirby Creek is made up of two rocks. The southeastern dikelike mass is a nepheline syenite, and the irregular part to the northwest is shonkinite.

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